Development and Application of Unsteady Flood Models Using Geographic Information Systems

by

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Abstract

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This document presents the application of two unsteady flow hydraulic models used for flood routing and visualization: the *MIKE 11* model from the Danish Hydraulic Institute (DHI) and the *HEC River Analysis System* model, better known as HEC RAS, from U.S. Army Corps of Engineer's Hydrologic Engineering Center. In this study, both hydraulic models use rainfall-runoff data in time series format from an existing *HEC Hydrologic Modeling System* (HEC HMS) model. The approach for both models leads to the spatial integration of unsteady flow simulations into a geographic information system (GIS) for flood visualization and animation. The study area applied to both models is the Mill Creek Watershed located in Cincinnati, Ohio. The Mill Creek watershed area is approximately 165 square miles consisting of 28 main stream miles. The study area used for the hydraulic models, referred to as the Primary Damage Center, is approximately 5.3 square miles in area consisting of 3.97 stream miles. The results found from this project support an on-going flood analysis study conducted by the Louisville District, U.S. Army Corps of Engineers. The primary source for the data used in the project was the Louisville District.

The study's focus was on 1) the development of an accurate and workable digital terrain model of the study area; 2) the development of a MIKE 11 model based on surveyed, stream cross-section data; 3) the development of a HEC RAS model based on stream cross-section data extracted from the terrain model; and 4) the creation of flood animations from the two hydraulic model simulations. The results

of this study provide information on the two unsteady flow hydraulic model methods as well as what advantages they have over steady flow hydraulic models.

The MIKE 11 model's stream geometry was based on surveyed data, which did not extent over the full width of the inundated flood plain. The HEC RAS model's stream geometry was extracted from the digital terrain model, which ensured that the flood plain's extent was fully accounted for. The results were faster flood wave attenuation, higher maximum water surface elevation, and shorter flood duration for the MIKE 11 model simulation as compared to the HEC RAS simulation. The results of the HEC RAS unsteady flow model were also compared to the HEC RAS steady flow model based on steady flow peak runoff discharge values. The unsteady flow hydraulic model's maximum water surface elevation was less than the steady flow hydraulic model's water surface elevation because the steady flow hydraulic model assumes peak runoff occurs simultaneously in the individual drainage basins within the watershed, while the unsteady flow model more closely mimics the movement of the flood wave through the drainage area.

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Chapter 1: Introduction

Flood analysis assists decision makers with the prevention and prediction of flood events. Computer modeling techniques have assisted engineers with determining more accurately where and when flooding may occur. Computer models for the determination of flood effects require four parts: 1) the hydrologic model which develops rainfall-runoff from a design storm or historic storm event, and 2) the hydraulic model which routes the runoff through stream channels to determine water surface profiles at specific locations along the stream network, 3) a tool for floodplain mapping and visualization, and 4) the extraction of geospatial data for use in the model(s). Most of the previous hydraulic modeling techniques use one-dimensional (1-D) steady-state flows measured at a specified point in time. Since flows in streambeds are naturally random and unsteady, steady-state methods do not always accurately depict water surface profiles. The steady-state modeling technique is also limited by how the modeler spatially synchronizes the rainfall-runoff routing for multiple drainage basins at a specified point in time. Such methods are subject to human error and can be very time consuming.

Developments in fully dynamic, unsteady models have provided engineers with highly accurate hydraulic modeling methods that result in graphical two- and three-dimensional visualizations for the purpose of analysis. The key to graphical visualizations in dynamic modeling is the inclusion of time-series data within a spatial interface, like a Geographic Information System (GIS). The Danish Hydraulic Institute (DHI) is one of the world-leading software developers for incorporating water resources related time-series data into modeling. DHI's MIKE 11 hydrodynamic model uses 1-D implicit, dynamic wave routing based on the St. Venant equations for unsteady flow. Additionally, DHI's MIKE 11 GIS extension to ESRI's Arcview GIS interface allows the user to import MIKE 11 model simulations in a time-series format into the Arcview GIS spatial environment.

The Army Corps of Engineers' Hydrologic Engineering Center has recently revamped their widely used 1-D, steady-state HEC RAS modeling software. The HEC RAS 3.0 version can also run 1-D unsteady flow simulations. The unsteady flow is processed in HEC RAS using the UNET algorithm developed by Dr. Robert L. Barkau (UNET, 1997). Like DHI's MIKE 11 model, UNET is a 1-D unsteady flow model that can simulate flow in a complex network of open channels. Unlike MIKE 11, the UNET algorithm can include off-channel storage and flood plain storage areas in the model.

This study involved the development and application of the two unsteady flow models mentioned previously. The models were applied to a critical location within the study area. Discharge hydrographs from the HEC HMS hydrologic model were extracted and imported into both models. The time-series results from both unsteady flow models were imported into Arcview GIS using corresponding Arcview extensions to develop floodplain determination and visualization in a spatial environment.

1.1 Objectives

The primary research objective was to develop flood visualization tools from the two modeling techniques of the Mill Creek Watershed for the Louisville District. To attain this objective, completion of the following steps was required:

1. Develop a MIKE 11 unsteady flow model for a section of the stream network within the Mill Creek Watershed using data obtained from the Louisville District's Engineering Division.

2. Develop a HEC RAS unsteady flow model for the same section of stream network

as the MIKE 11 model.

3. Incorporate existing results of the Mill Creek Watershed's HEC HMS model into both the MIKE 11 and HEC RAS models for the 25-yr flood event of April 1998.

4. Develop digital terrain models for the same portion of the Mill Creek Watershed in which the MIKE 11 and HEC RAS modeled stream network exists. Incorporate stream characteristics into both terrain models.

5. Create two- and three-dimensional flood animations of the April 1998 storm from both models for future analysis and public presentations.

6. Determine benefits and limitations of using the two modeling methods.

To complete these tasks, an extensive amount of data stored in different formats was required. Current data processing and management practices were used in most cases. Otherwise, dissimilar data sources and modeling software required additional data processing solutions and conversions.

1.2 Study Area

The Mill Creek Watershed is located in Butler and Hamilton Counties in southwestern Ohio. It flows from the southeastern part of the rural Butler County in a southerly direction across the highly urbanized Hamilton County and through the city of Cincinnati to its confluence with the Ohio River. The total fall in elevation from the headwaters of Mill Creek to the Ohio River is about 250 feet over an approximate distance of 28 stream miles, with an average gradient of 8.9 feet per mile (0.16%). The watershed is in the northeastern finger of the Hydrologic Unit Code (HUC) #05090203. In 1997, the environmental interest group, *American Rivers*, designated Mill Creek as "the most threatened urban stream in North America" (Project Study

Plan, 1997).

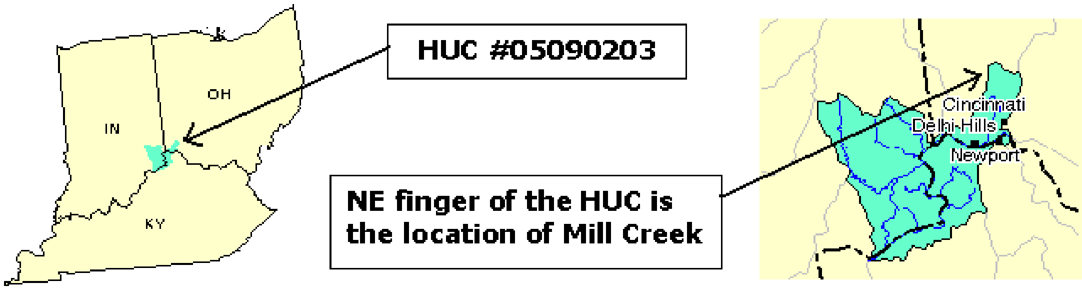


Figure 1-1. Location of the Mill Creek Watershed in Cincinnati, OH.

Flooding has been a significant problem for the Mill Creek Watershed for some time. The most damaging flood occurred in January 1959. Since then, there have been numerous floods of lesser magnitude. Over bank flooding occurred in some areas as late as the spring of 1998.

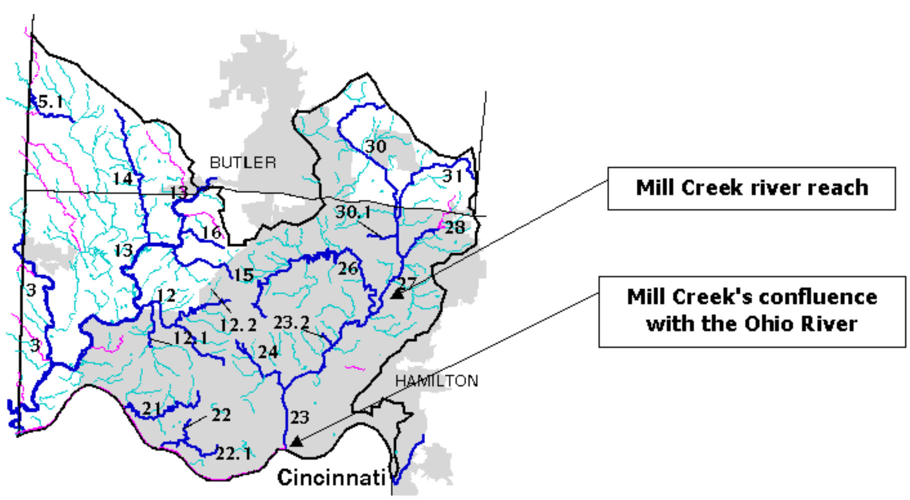


Figure 1-2. Mill Creek location with respect to the Ohio River.

Based on a Local Cooperation Agreement in 1975, construction by the Corps of Engineers to reduce flooding in the watershed was initiated in 1981 and eventually suspended in 1992, with approximately 50% of the construction complete. The construction was suspended for a number of reasons. The Assistant Secretary of the Army for Civil Works suspended the project because: 1) there were problems in acquiring real estate and relocations for the remaining sections of the creek requiring construction, 2) project costs had soared over 126% of the authorized amount, 3) there was likely contamination of the water from non-point source pollutants from old landfills along some of the uncompleted portions of the reach, and 4) there were problems maintaining and operating the sections where construction was completed (Project Study Plan, 1997).

In 1997, a reevaluation study was performed. The effort showed that even with the partially completed plan in place that significant damage would occur from a flood with a 50% chance of occurrence. Total residual damage is estimated over $486 million for the 1% chance flood and over $910 million for the 0.2% chance flood. Total expected annual damage for the flood area is estimated over $32 million, almost 96% of the damage being commercial or industrial (Project Study Plan, 1997).

Although completion of the previous plan is economically feasible, the Louisville District believes that a more cost effective and environmentally acceptable plan can be formulated. There is currently strong local support in Cincinnati to address the environmental needs of Mill Creek.

This study models unsteady flow for a 25-yr storm event for a 3-mile section of Mill Creek referred to as the Primary Damage Center (PDC). After numerous flood events in recent years, approximately 90% of the overall damage from flooding in the watershed occurs within the PDC. The PDC is located in the northern part of the Mill Creek watershed and is a highly industrialized area. The average gradient of Mill Creek in the PDC is 0.017%. Since the PDC can almost be considered as level ground, the area acts almost like a reservoir after intense storms. Most of the facilities have tried to accommodate for the flood problems by building levees around their property's boundaries.

For the unsteady flow model, the stream network in the PDC study area will have two streams and one tributary. In the northern portion of the PDC, East Fork flows southward from the northeast portion of the study area into Mill Creek. The stream flow from additional tributaries along Mill Creek in the PDC is accounted for as lateral inflow data from the hydrologic model.

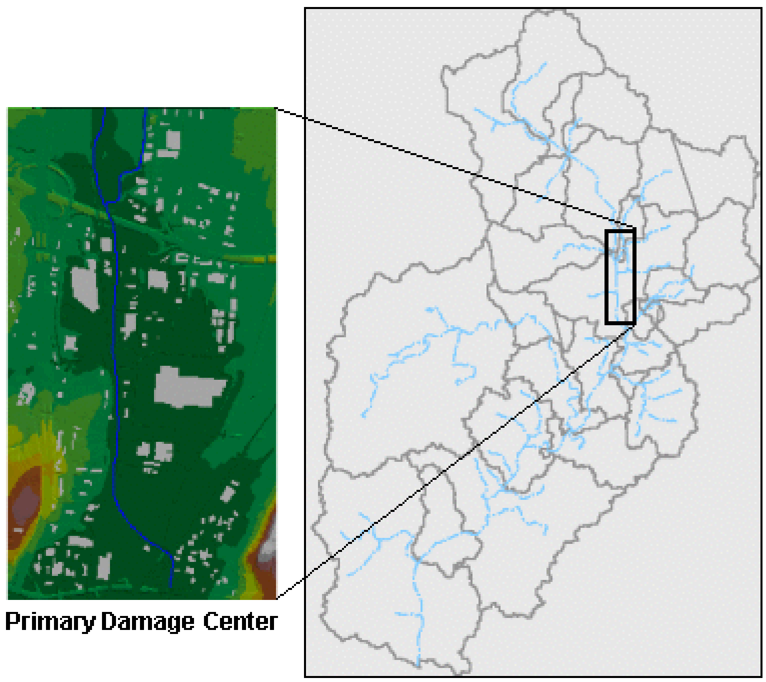


Figure 1-3. Location of the Primary Damage Center in the Mill Creek Watershed.

1.3 Structure of Report

This report documents the data development and implementation of a MIKE 11 and HEC RAS unsteady flow model for flood visualization. The report is divided into eight chapters. Chapter 2 includes a review of previously used methods in literature related to this research. Chapter 3 is a discussion of the data used for both models. The technical capabilities of the computer programs used during the research are outlined in Chapter 4. Chapter 5 discusses the development of the study area's digital terrain models, which use different formats for the two models. Application of the data and program interface of the MIKE 11 model is documented in Chapter 6. Chapter 7 is the documentation of the HEC RAS model application, and Chapter 8 presents the results and conclusions of the project.

Information supplemental to the results of this report are included as appendices. Appendix A includes the conversion of HEC-2 River Station identification numbers to MIKE 11 Chainages for the purposes of geo-referencing. Appendix B provides the *Visual Fortran* program used to convert HEC RAS cross-sections, in text format, into a MIKE 11 cross-section file. Appendix C provides the MIKE 11 cross-section file created by the Visual Fortran program previously discussed. Appendix D is the initial HEC RAS geometry file created from the HEC-2 data files. Appendix E shows the time-series data transferred from the HEC HMS hydrologic model into the MIKE 11 and HEC RAS flow model. Finally, Appendix F is a data dictionary describing the data used in the project.

Chapter 2: Literature Review

2.1 Flood Modeling

Incorporating hydraulic model results into a GIS environment has improved flood analysis in recent years. Numerous modeling techniques have been interconnected in an attempt to find an optimum combination of various methods. In an attempt to connect hydraulic results to a spatial interface, Djokic (1994) developed an interface between the Hydrologic Engineer Center's HEC-2 1-D, steady-state hydraulic model and the Arc/info spatial GIS. The interface, known as ARC/HEC2, exports the terrain data from Arc/info into HEC-2. The ARC/HEC2 interface converts HEC-2 water surface elevations into GIS coverages in Arc/info.

Evans (1998) developed a data exchange format to transfer physical element descriptions between hydrologic and hydraulic software packages and GIS software. The package studied was HEC RAS, with the ability to import cross-section locations as XYZ coordinates from terrain models to develop channel and reach geometry. Upon completion of the hydraulic calculations, HEC RAS exports the data back to a GIS for comparison with the terrain model. In 1998, ESRI translated and improved Evans' code and added some utilities to facilitate its use. The result was an Arcview GIS extension called *AVRas*.

Tate (1999) further investigated how to improve upon the HEC RAS model's accuracy by incorporating field surveyed, stream geometry and control structures into a GIS-based terrain model. His research led to the development of *Avenue* scripts for Arcview GIS that integrate such data. The terrain model Tate used for his study was based on very accurate digital orthography. Andrysiak (2000) applied Tate's Avenue scripts to a larger study area using a digital elevation model (DEM) with 30-meter accuracy as the terrain model. When studying both cases, one can deduce that terrain model refinement is limited to the accuracy of the data. In addition, accuracy of the geo-referencing of the surveyed cross-sections and control structures is imperative in the development of an optimum terrain model.

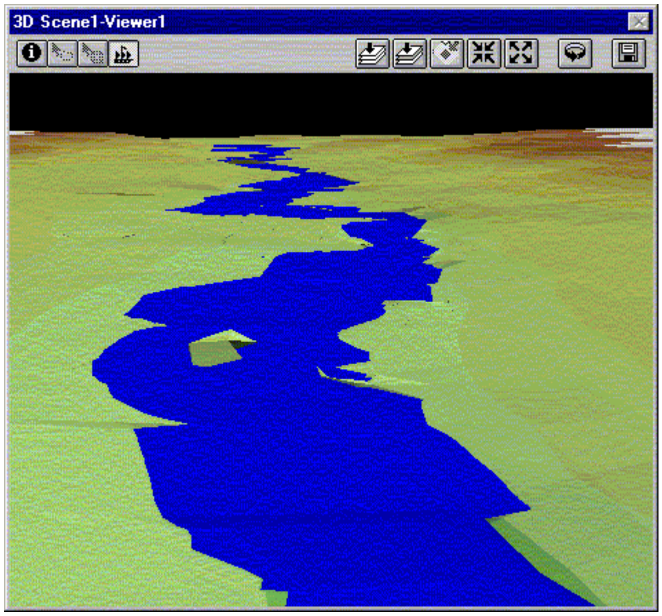


Figure 2-1. Channel geometry incorporated into a digital terrain model (Tate 1999).

Azagra-Camino (1999) focused on a smaller study area using more precise terrain data from the development of a Triangulated Irregular Network (TIN) in Arcview GIS. The TIN was created from aerial photography, which resulted in a highly accurate terrain depiction of the study area. Using the AVRas extension, Azagra-Camino extracted topographic information from the TIN and imported it as channel and stream geometry for use in the HEC RAS model. The flood visualization results provided highly accurate 2-D and 3-D flood maps. Azagra-Camino's method was limited to one output in time for each run from the steady state HEC RAS model, making the process of developing flood animations tedious. The animations he created required multiple runs of the HEC RAS model and importing the data into the TIN. Additionally, Azagra-Camino extracted the cross-section data directly from the terrain model. Since the terrain data was based on aerial photography, the cross-section data did not account for existing water surfaces in the stream channel when the photographs were taken. Thus, results from his HEC RAS model may not have been accurate.

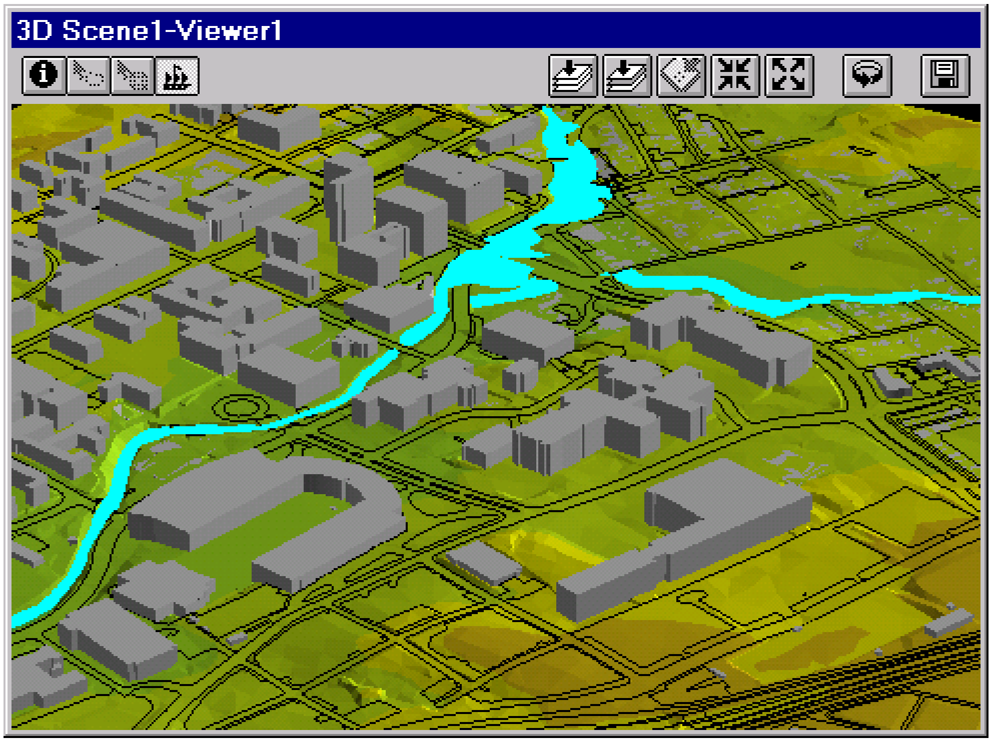


Figure 2-2. Flood visualization using AVRas and a TIN (Azagra-Camino 1999).

The previously mentioned 1-D flood modeling methods used steady state hydraulic modeling to determine stream water surface elevations and flows. The steady-state models do not take into account all of the hydrodynamic effects that more accurately depict actual flood events. The development of 2-D and 3-D animations from steady state models also requires numerous runs at different flow inputs. This makes flood animation development tedious and very time consuming.

2.2 Dynamic Models

More complex methods of 1-D hydraulic modeling have become more accepted during recent years, as windows-based computer technology has emerged as the optimum graphical analysis tool. Dynamic wave routing was first used in the early 1950s, but was not widely accepted as a flood analysis method. Computer limitations and the complexity of solving methods initially made dynamic wave routing unpopular for practical applications.

In 1871, Adhemar Jean Claude Barre de Saint-Venant derived the *continuity* and *momentum* equations for 1-D unsteady flow in an open channel, known as the St. Venant equations. The equations he derived assume uniform cross-sections and bed slope for a segment of open channel with no flow above the banks. Danny L. Fread (1976) further investigated the St. Venant equations and developed an implicit method of solving the dynamic wave for the modeling of meandering streams. He distinguished left and right flood plains from the flow channel in a stream's cross-section. The method was used to solve for the unknowns h (water surface elevation) and Q (stream flow) for specified points along the stream over a series of time steps. Fread first approached the problem by dividing stream channels into two conceptual channels – the stream channel and floodplain. He made four additional assumptions to simplify the 1-D flow problem: 1) the water surface at each cross-section is horizontal (normal to the direction of flow), 2) the momentum exchange between the stream channel and floodplain is negligible, 3) the flow is distributed to the stream channel and floodplain according to conveyance, and 4) the bed channel slope is small (denoting subcritical flow). These assumptions led Fread to an implicit method to solve the St. Venant equations using a finite difference solution.

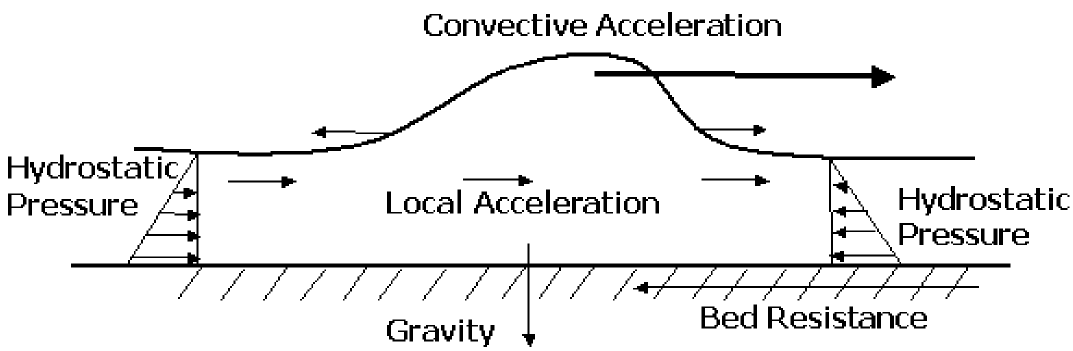


Figure 2-3. Finite element of a stream channel with force terms.

To better understand unsteady flow equation terms, consider a finite segment of the stream as shown in Figure 2-3. There are five acceleration and pressure terms that act on the control volume: *convective acceleration*, *local acceleration*, *hydrostatic pressure*, *bed resistance*, and *gravity*. The convective acceleration, local acceleration, and hydrostatic pressure terms are important to dynamic wave motion because they account for pressure and inertial forces which characterize the movement of a large flood wave in the stream (Chow et al 1988). The equations simplify to the following:

Continuity equation

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = q \quad (1)$$

Momentum equation

$$\frac{\partial Q}{\partial t} + \frac{\partial(\beta Q^2/A)}{\partial x} + gA\frac{\partial h}{\partial x} + \frac{gQ|Q|}{C^2AR} = 0 \quad (2)$$

where

- Q: discharge
- A: flow area
- q: lateral inflow
- h: stage above datum
- C: Chezy resistance coefficient

R: hydraulic radius

g: gravity constant

β: momentum coefficient

For Fread's methodology, the above equations were separated between stream channel and flood plains. The momentum coefficient, also known as the Boussinesq coefficient, accounts for uniform distribution of velocity at a cross-section. Its value ranges from 1.01 for straight prismatic channels to 1.33 for river valleys with flood plains (Chow et al 1988).

Fread's methodology led to the development of the U.S. National Weather Service's (NWS) *DWOPER* (Dynamic Wave Operational Model) and *DAMBRK* models. The DWOPER and DAMBRK models use the implicit method for solving the St. Venant equations for unsteady flow. The DAMBRK model was used by the NWS to analyze floods resulting from dam breaks. The NWS models eventually led to the development of the *FLDWAV* model by Fread (1985). FLDWAV is a dynamic wave model for 1-D unsteady flows for a single stream or a stream network. Like the DWOPER and DAMBRK models, it is based on an implicit finite-difference solution of the St. Venant equations.

Expanding on Fread's work, Robert L. Barkau (1982) defined a new set of equations that were more convenient to solve by computation methods. He combined the convective terms for both the floodplain and channel using a velocity distribution factor. Barkau also replaced the friction slope (bed resistance term) with equivalent force terms. His work is the basis of the Hydrologic Engineering Center's 1-D, unsteady flow model called *UNET*. HEC recently improved upon HEC RAS by including unsteady flow using the UNET program as an extension to the software. The unsteady flow option currently exists for HEC RAS version 3.0. Time-series water surface elevations results developed from a HEC RAS model can now be imported into Arcview GIS using the HEC *GeoRAS* extension, a new version of AVRas.

In Europe, the Danish Hydraulic Institute (DHI) developed the MIKE 11 hydraulic model in 1987 and it became a widely applied 1-D dynamic modeling tool for rivers and channels. Its ability to simulate unsteady stream flows for specified time durations and time steps currently make it a powerful graphical tool. When using the MIKE 11 GIS extension for Arcview GIS, time-series results from a MIKE 11 simulation can be imported into a GIS-based digital terrain model for flood visualization.

Carr (1989) and Kjelds (1997) have previously incorporated a DHI-developed hydrologic model, *MIKE SHE*, with the MIKE 11 and MIKE 11 GIS interfaces for the presentation and analysis of flood impacts. Because of the commonality of the hydrologic and hydraulic models, DHI-based models have been successfully updated into a real-time flood-forecasting tool, known as *FLOOD WATCH*.

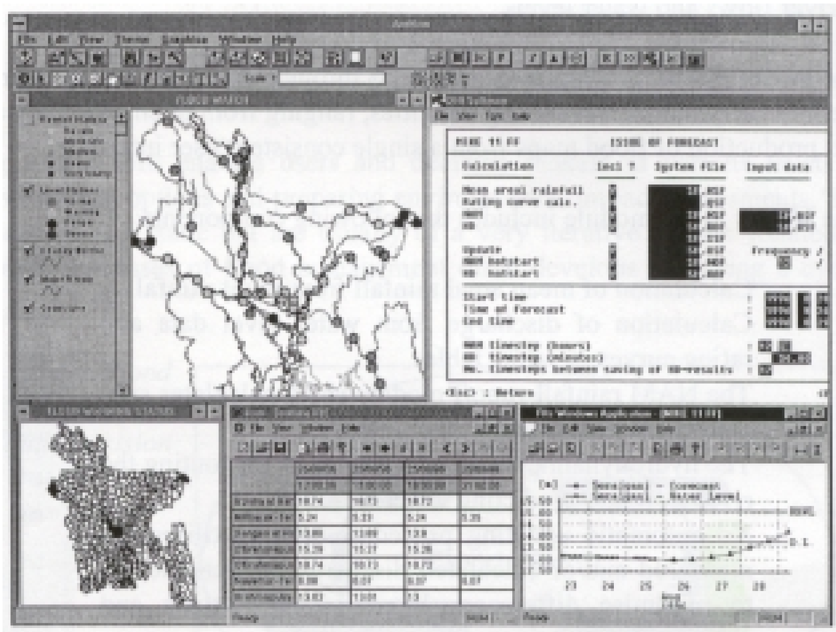


Figure 2-4. FLOOD WATCH applied to a region in India (Kjelds 1997).

Flood visualization using the HEC RAS and MIKE 11 models are limited to the accuracy of the topographic data from the terrain model and the continuous availability from numerous gage stations. Further discussion of the multiple data sources used in this project are addressed in Chapter 3. If stream geometry and topographic data are obtained from different sources and are not included in the terrain model, then flood visualization results from the hydraulic model can be affected. Flood visualization can still provide some validity, especially when analyzing a complete watershed system where multiple rainfall-runoff inputs are sequenced in time.

Chapter 3: Data Discussion

This chapter analyzes the data used in this project. The first section discusses the data requirements for the two unsteady flow models applied in this project, and the last section discusses the source of the data used and the processing of that data. The inclusion of the data in the models is described in Chapters 5 through 7.

3.1 Data Requirements

The data used in this project is classified into three sections: hydraulic, hydrologic, and spatial data. Each section is examined below. Discussion of all data is applied to both the MIKE 11 and HEC RAS models, unless otherwise specified.

3.1.1 Hydraulic Data

Unsteady 1-D flow models require, at a minimum, three forms of hydraulic data: 1) stream geometry, 2) streambed resistance factors, and 3) time-series flow and/or stage height boundary conditions. For both models, streambed cross-sections at locations along the network make up a significant portion of the overall geometry data. Cross-sections act as upstream and downstream boundaries for each finite element in the model. Cross-sections provide the cross-sectional area data required for unsteady flow computations.

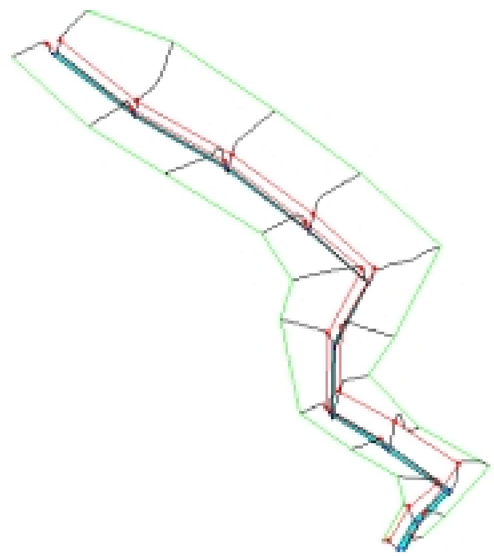


Figure 3-1. 3-D depiction of a stream with cross-sections in HEC RAS.

The network, or stream centerline, of a 1-D flow model can theoretically be modeled as a straight line since natural dispersive effects of flow are not considered. For this project, the stream network contains x- and y-coordinate data in a 2-D plane so as to spatially connect the unsteady flow models to the corresponding terrain models. To accurately depict historic flows in an unsteady flow model, cross-sections must b accurately referenced along the network. For the MIKE 11 model this reference system is referred to as *Chainages*, and starts from the most upstream location of a stream and heads downstream to its confluence. Chainage values are derived the same way for any additional branches within the hydraulic model. Chainage values are measured in meters.

When using the HEC RAS model, the network referencing of the cross-sections is known as *River Stations*, and runs opposite of Chainages (starts at a stream's confluence and goes upstream). Unlike Chainages, River Stations can use any sequential method to identify cross-sections, as long as downstream reach lengths from each cross-section to the next are known.

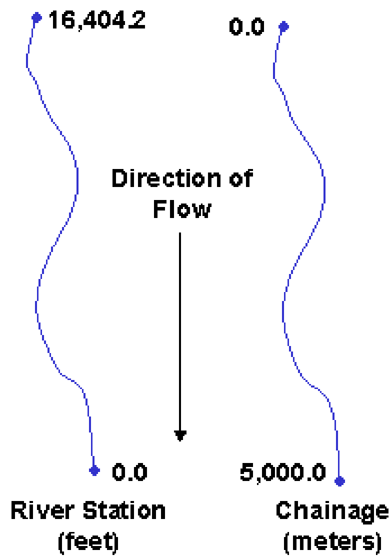


Figure 3-2. Comparison of Chainage and River Station network referencing.

Bed resistance factors are also necessary when defining hydrodynamic parameters for unsteady flow models. The resistance factors are used in the bed resistance term in the St. Venant momentum equation. In MIKE 11, the bed resistance factors are differentiated between the streambed and flood plains. Thus, the location where the streambed ends and the left and right flood plains begin must be defined in each cross-section. Resistance factors can be defined in the MIKE 11 model from one chainage value to another for a segment of the reach, as well as locally per individual cross-section. Resistance factors can be inputted as Manning's *n*, Manning's *M*, or Chezy's *C* values (MIKE 11 automatically converts resistance factors to Chezy's *C* values).

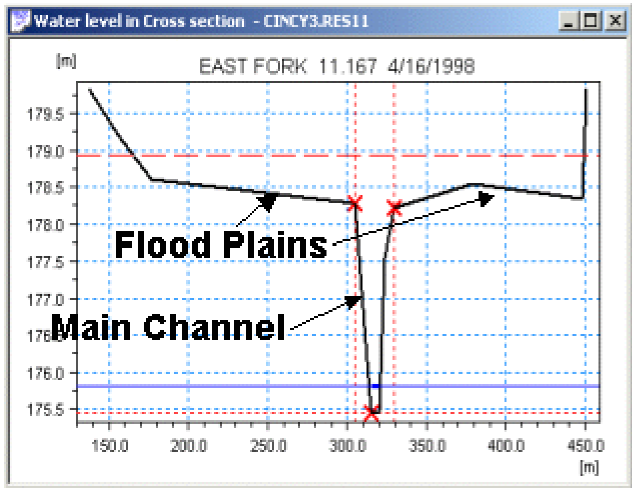


Figure 3-3. Differentiation of streambed and flood plain resistance in MIKE 11.

In the HEC RAS model, bed resistance is defined at each cross-section as Manning's *n* values. Unlike the MIKE 11 model, defining the bed resistance for each cross-section is not limited to only the streambed and flood plains. Differences in resistance can be defined for additional portions of each cross-section as well.

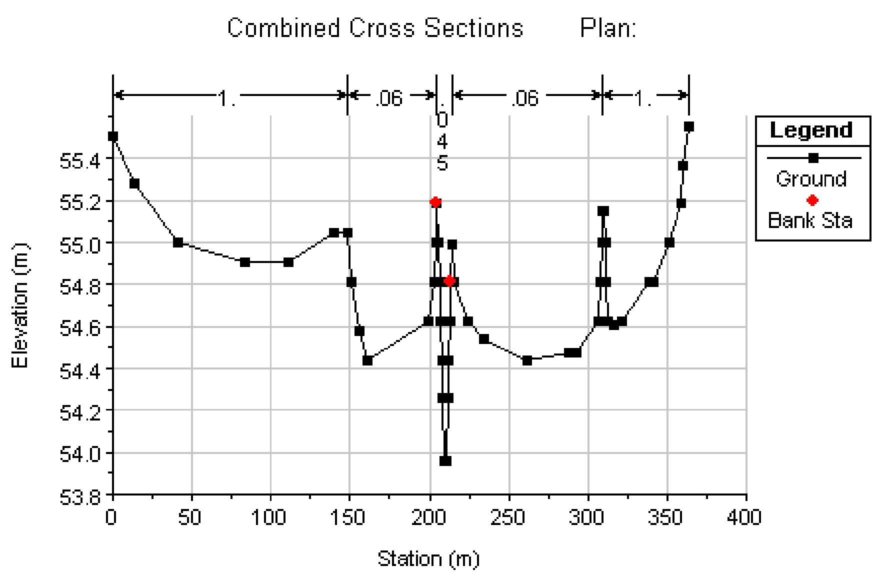


Figure 3-4. HEC RAS cross-section with Manning's *n* values shown above the graph.

The final hydraulic data requirement for unsteady flow models is the boundary conditions. Unlike steady-state conditions, a boundary condition for unsteady flow may be in time-series format defined by a user-specified time range and time step. Time-series boundary types are *discharge (Q)* and *stage heights (h)*. Another commonly used boundary type not in time-series format is a *stage-discharge* relationship known as a *rating curve*. For the MIKE 11 model, the boundary conditions are limited to *Q* hydrographs for upstream boundaries and *h* hydrograph for downstream boundaries. When *h* hydrographs do not exist, the data can be interpolated using the downstream cross-sections rating curve and the existing flow conditions. In HEC RAS, upstream boundaries are defined as *Stage*, *Flow* or *Stage and Flow* hydrographs; downstream boundaries are defined as *Stage*, *Flow*, *Stage and Flow*, *Rating Curve*, or *Normal Depth*.

Boundary conditions usually depict a flood event for a specified design storm and are obtained from upstream and/or downstream gage station data. The boundary conditions can also be determined from hydrologic models as well. When hydrologic model data is incorporated, lateral runoff hydrographs at watershed outlets along the network provide a more accurate depiction of runoff for that specified storm event.

Initial conditions depict base flow conditions prior to a storm event, and are used in MIKE 11 to optimize the model's performance. When modeling a storm event, the MIKE 11 model can first be used to establish base flow conditions from the gage or hydrologic model data. The simulation is known as a *hotstart* and is explained in more detail in Chapter 5.

3.1.2 Hydrologic Data

As previously discussed, hydrologic data is the output response of a precipitation (storm) hyetograph input to a watershed system. The output response is a flow (runoff) hydrograph for each individual watershed in the system. There are numerous methods used to model hydrology for a specified watershed.

In MIKE 11, a hydrologic model can be developed directly from the MIKE 11 software interface using the *Rainfall Runoff* file. The NAM (lumped, conceptual model), UHM (unit hydrograph method), or SMAP (soil moisture accounting model) modeling methods can be used. Limitations to the *Rainfall Runoff* file are hydrologic attributes, like a drainage basin's area and Curve Number for example, must be inputted into the file by hand.

For the HEC RAS model, hydrologic data can be imported into the model's flow data from the HEC *Hydrologic Modeling System* (HMS). Results from the HEC HMS model are imported by using the HEC *Data Storage System* (DSS) utility. Further discussion and implementation of the DSS utility can be found in Chapter 7. The HEC HMS model has a wide range of hydrologic modeling methods. Loss rates can be determined using either the *SCS Curve Number* or the *Green and Ampt* method. Transformation of the rainfall into a runoff hydrograph can be accomplished using the *UHM*, *Clark*, *Modified Clark*, or *Snyder* hydrographs (HEC-HMS, 1998).

When incorporating hydrologic model results into an unsteady flow model, the key is to accurately geo-reference each watershed outlet to the stream network. Most hydraulic models have means to import or geo-reference a hydrologic model's results, as long as the flow model and hydrologic model were developed and packaged as supporting software tools. This is the case for both the MIKE 11 and HEC RAS models.

Since this project's focus is on unsteady flow modeling, the hydrologic results for both hydraulic models were derived from the same hydrologic model, previously developed by Andrysiak (2000). Andrysiak's HEC HMS model results were imported directly into the HEC RAS model using the DSS utility. To integrate the hydrologic results into the MIKE 11 model, the resulting flow hydrograph at each watershed outlet was geo-referenced by using the same x- and y- coordinate plane for both the MIKE 11 stream network and HEC HMS watershed schematic.

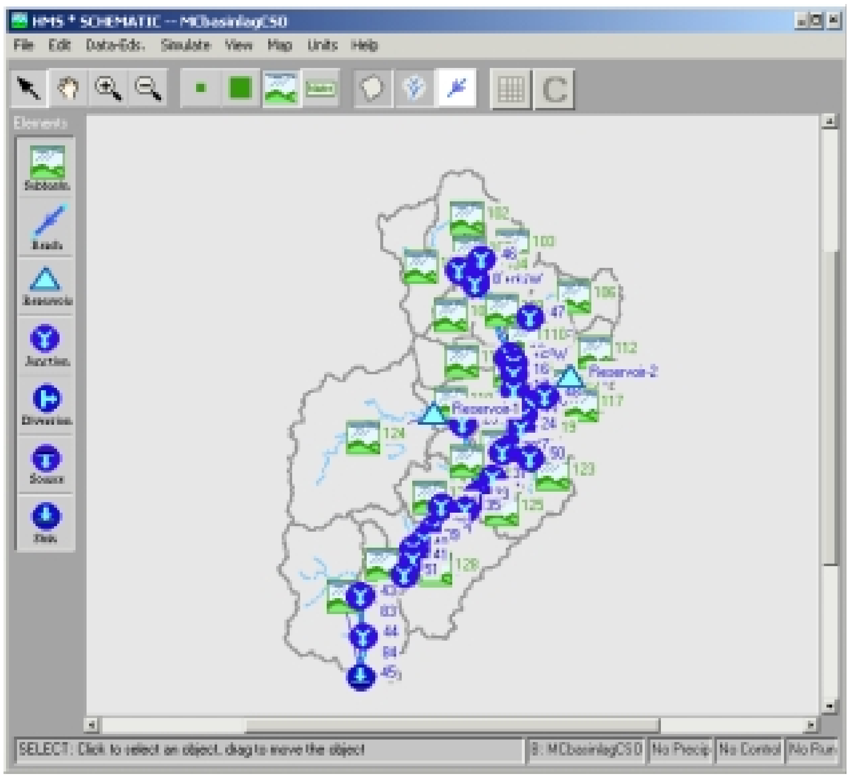


Figure 3-5. Schematic view of the HEC HMS model developed by Andrysiak (2000).

3.1.3 Spatial Data

Visualization of floods in Arcview GIS requires a detailed representation of the terrain to accurately depict flood inundation. As the study area's size increases, computer memory requirements increase and software-processing speeds decrease substantially. The modeler must find a medium that best fits modeling requirements and computer capacity.

The critical spatial data necessary for flood visualization are used to develop a terrain representation of the study area. The data is usually available for the continental United States as grid- or vector-based GIS themes. At a minimum, a *Digital Elevation Model* (DEM) can be used to develop the terrain model, but is not the optimum data source. Availability of more accurate terrain depictions, like digital orthographic photo images, vector-based contour themes, or Triangulated Irregular Networks (TINs) usually provide more accurate terrain representations. TINs are 3-D GIS themes created by a random mesh of triangles that best fit the depiction of the terrain. An example of a TIN is shown in Figure 3-6. Additional themes in GIS like roads, buildings, levees, and railroads, can also be integrated into the spatial model to improve upon the accuracy of the terrain model.

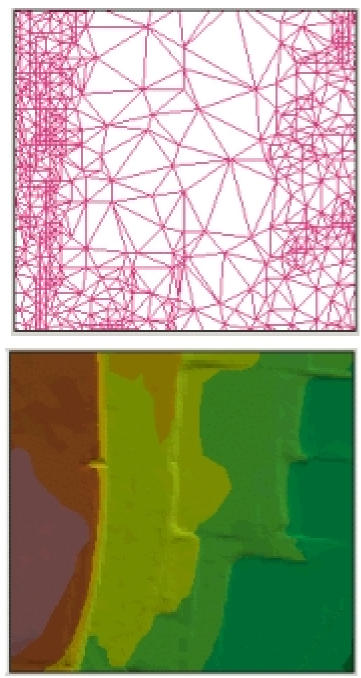


Figure 3-6. A triangular mesh and TIN theme in Arcview GIS.

3.2 Data Sources and Processing

The first step in data processing for spatial modeling is to determine a common coordinate system for data sources. Once that is established, identification of data sources and initial processing can begin. The sources and processing of the data for use in this project are categorized into three sections – terrain data, geometric data, and flow data. For 1-D flow models, the processed data is organized and understood using stream network referencing. Network referencing is the key step to integrating unsteady flow model results with the terrain model in Arcview GIS. This section discusses this project's data development.

3.2.1 Coordinate System

The project required a common projection to spatially correspond the unsteady flow model results to the GIS environment. Since both of the unsteady flow models use an XYZ coordinate system, a Cartesian coordinate system is required. The Ohio State Plane (OSP) Coordinate System for southern Ohio was used throughout the project. All the GIS themes were projected into OSP system using Arc/info, with the following formatted text file as the output projection properties:

```
output
projection LAMBERT
/* datum NAD83
zunits METERS
spheroid GRS1980
xshift 0.0
yshift 0.0
parameters
38.733333
40.033333
-82.5
38.0
600000
end
```

3.2.2 Terrain Data

The Louisville District provided the terrain data used in this study. The data included three vector-based Arcview GIS themes, depicting 1-ft contour lines for the

Primary Damage Center (the model area). The three themes were merged into one single theme in Arcview. The terrain model created from the 1-ft contour lines consisted of 6,028,127 triangles within the TIN mesh (240 MB of computer memory). Because of limitations with computer memory capacity, a new terrain model was required. Deleting every other contour line in the study area's 1-ft contour theme revised the terrain data to a 2-ft contour theme. The new TIN-based terrain model was developed from the 2-ft contour theme. The development of the 2-ft contour theme and the TIN-based terrain model is explained in Chapter 5. The terrain model now consisted of 134,470 triangles in the TIN mesh, using 4.39 MB of computer memory. The result was an accurate terrain data depiction that could be effectively used within the processing constraints of the computer. A practical limit to the number of triangles to use in the TIN mesh is 500,000 triangles. Obviously this number can be adjusted based on computer speed, computer capacity, and modeler requirements.

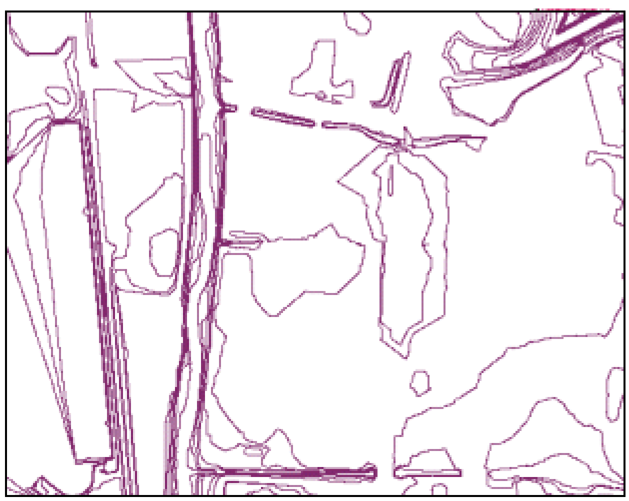


Figure 3-7. Portion of the 2-ft contour theme depicting the Primary Damage Center (study area).

Additional Arcview GIS themes can be used to further improve the terrain data. The building and street themes of the study area were also provided by the Louisville

District. Existing buildings that lie within a flood plain can create a physical barrier to high stage flows. By incorporating buildings into the terrain model, the stream cross-sectional geometry used in the unsteady flow model can change accordingly. Buildings can divert water flow that may have an impact on the flow model's results. Building themes can also provide a visual reference when delineating floods with the terrain model.

The street theme also has a purpose for use in flood visualization, mainly as a reference tool. When the network referencing of cross-sections, control structures, and watershed outlets are not obvious to the modeler, a street theme can assist with referencing where the street theme intersects with the stream network. When visualizing the results of the flow model in Arcview GIS, streets can assist an observer unfamiliar with the study area by providing a spatial reference for the terrain model. The street theme was unnecessary in the development of the terrain model, since the contour data already contains the topography of the roads.

3.2.3 Geometric Data

The geometric data used for the unsteady flow models consists of three basic data sets: 1) the stream network, 2) cross-sections of the stream network, and 3) channel and flood plain resistance factors.

3.2.3.1 The Stream Network

The stream network for 1-D unsteady flow models can be created directly in the model or imported from another source. Since the model is 1-D, the model does not differentiate whether the stream is a straight line or has an x- and y-coordinate system related to the terrain model. As long as downstream reach lengths for the channel and flood plain flow paths from cross-section to cross-section are known, and all other geometric data is accurately referenced along the network, the flow model will provide the same results. For this study, the x- and y-coordinates for the network are necessary to integrate the flow model's simulation results into the GIS spatial environment.

One method of developing the stream network is to digitize a polyline in Arcview GIS using orthographic photo images or U.S. Geological Survey (USGS) quadrangle maps in Arcview GIS. Another method is to clip a section of an existing river network theme that corresponds to the terrain model. Existing network themes can be downloaded from the Internet for use in Arcview GIS. One network theme, called an RF3 river reach file, is downloadable from the Environment Protection Agency's (EPA) Office of Water web site (http://www.epa.gov/ow/soft.html) and contains all the river networks existing in maps of the continental United States at a 1:100,000 scale. An even more accurate network file can be found from the National Hydrography Dataset (NHD), which can be obtained from the USGS web site, http://nhd.usgs.gov/. When working with smaller study areas with more detailed data, RF3 and NHD data may require some editing to better fit the stream network to the terrain model's stream channel.

To create a stream network that fits the same coordinate system as the terrain data, the stream network was digitized from the terrain model in this study. An RF3 river reach file was initially used, but it did not correspond with the terrain model's stream channel. A point theme was created from the RF3 river reach file and adjusted to fit the stream channel's centerline. The stream network was digitized from point to point along the stream channel. The same stream network was used for both the MIKE 11 and HEC RAS unsteady flow models.

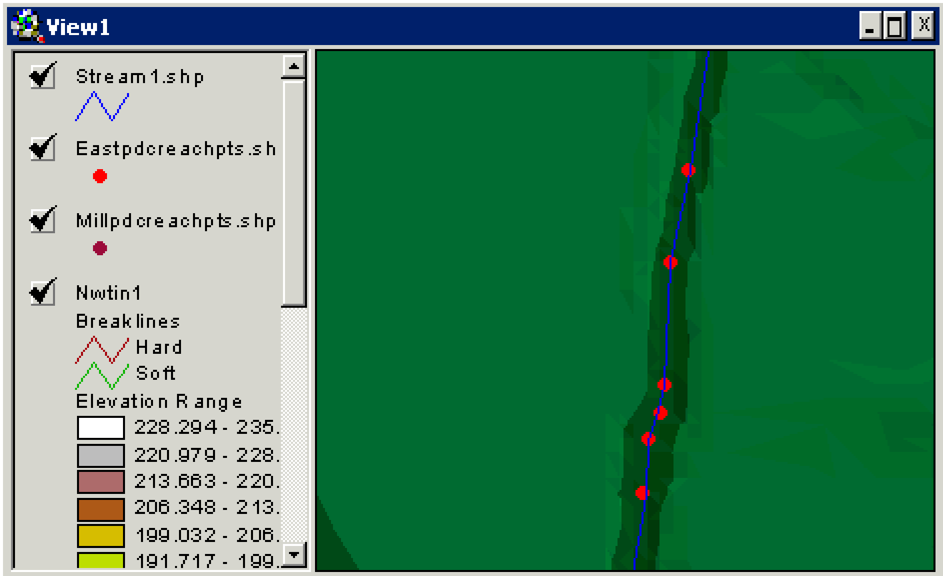
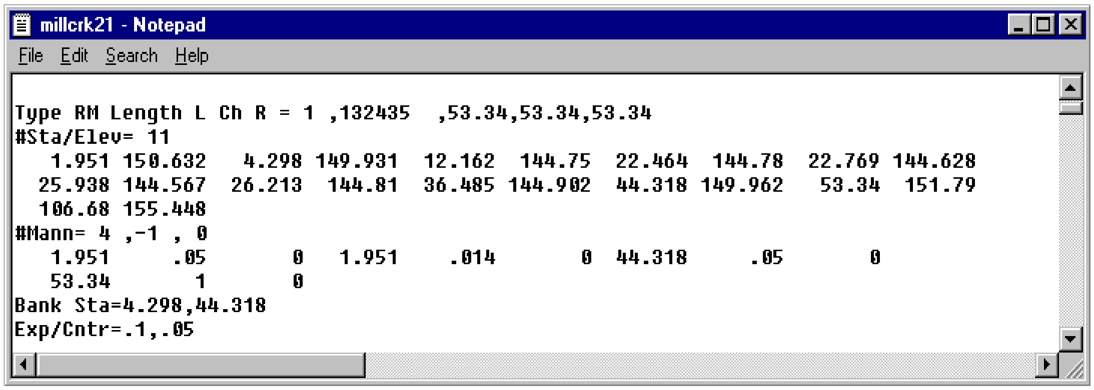


Figure 3-8. Stream network digitized in Arcview GIS using a point theme.

3.2.3.2 Cross-section Data

The Louisville District provided two HEC-2 text files that contained cross-sectional data for the stream network. The HEC-2 files were imported into the HEC RAS model to develop geometry files. The geometry files contain x- and z-coordinate profiles of cross-sections at specified locations along the stream network. The resistance factors were also included in the files. The geometry files were saved as .G01 files in the HEC RAS model.



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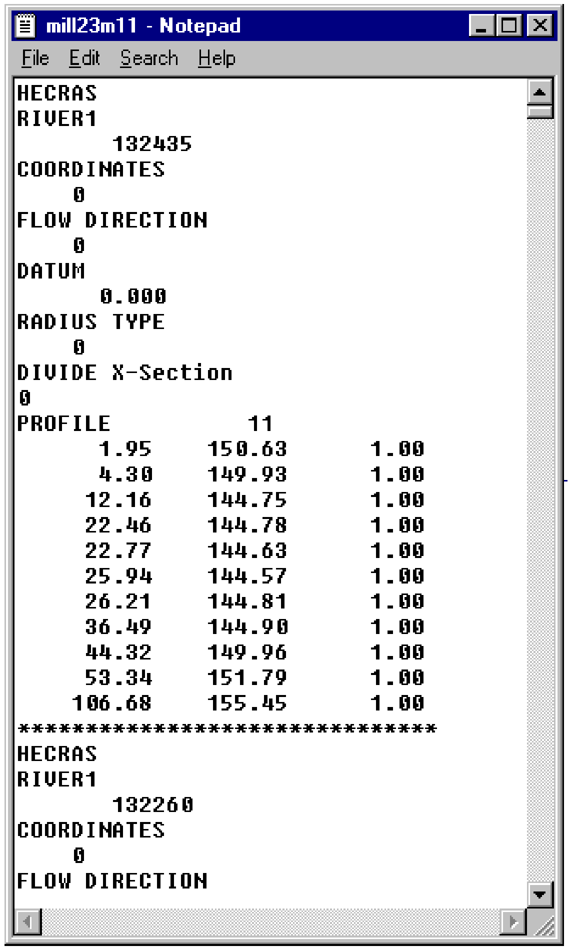
File Edit Search Help

```
Type RM Length L Ch R = 1 ,132435  ,53.34,53.34,53.34
#Sta/Elev= 11
   1.951 150.632   4.298 149.931  12.162  144.75  22.464  144.78  22.769 144.628
  25.938 144.567  26.213  144.81  36.485 144.902  44.318 149.962   53.34  151.79
  106.68 155.448
#Mann= 4 ,-1 , 0
   1.951     .05       0   1.951    .014       0  44.318     .05       0
   53.34       1       0
Bank Sta=4.298,44.318
Exp/Cntr=.1,.05
```

Figure 3-9. Example of cross-section data in a HEC-RAS .G01 text file.

The HEC-2 files also contained downstream reach lengths and a *River Station* designation for each cross-section for network referencing. This was important in the conversion process to MIKE 11, to ensure the cross-sections were properly referenced as *Chainages* along the MIKE 11 stream network. The conversion of the River Station designations to Chainages in MIKE 11 is shown in Appendix A.

Using a *Visual Fortran* program developed by Mr. Stefan Szylkarski from DHI, the .G01 files were converted into text files that the MIKE 11 software could read. The Visual Fortran developed is shown in Appendix B. The resistance factors were was not imported into the file, and are discussed in the next section.



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```
HECRAS
RIVER1
        132435
COORDINATES
     0
FLOW DIRECTION
     0
DATUM
       0.000
RADIUS TYPE
     0
DIVIDE X-Section
0
PROFILE          11
       1.95     150.63       1.00
       4.30     149.93       1.00
      12.16     144.75       1.00
      22.46     144.78       1.00
      22.77     144.63       1.00
      25.94     144.57       1.00
      26.21     144.81       1.00
      36.49     144.90       1.00
      44.32     149.96       1.00
      53.34     151.79       1.00
     106.68     155.45       1.00
*******************************
HECRAS
RIVER1
        132260
COORDINATES
     0
FLOW DIRECTION
```

Figure 3-10. Cross-section text file readable by the MIKE 11 software.

The HEC-2 cross-sectional data was not used for the HEC RAS model. Flood visualization using the HEC GeoRAS extension requires the geometry data to be extracted from the terrain model in Arcview GIS. Using the stream network previously developed, cross-section locations along the stream were manually digitized. River Station referencing and downstream reach lengths were automatically calculated by the HEC GeoRAS extension. This process is discussed in Chapters 4 and 7.

3.2.3.3 Channel and Flood Plain Resistance Factors

Channel and flood plain resistance factors for this study were also provided in the HEC-2 files as Manning's *n* values. For this project, the resistance data was inputted into the MIKE 11 and HEC RAS models manually.

HEC GeoRAS provides an option to extract the Manning's *n* values from Arcview GIS. If an accurate *Land Use* theme is available, the HEC GeoRAS extension will automatically calculate Manning's *n* values for each cross-section and export those values with the extracted geometry data into the HEC RAS flow model.

3.2.4 Flow Data

Flow data for both of the flow models consisted of the stream network's average base flows and runoff hydrographs derived from the hydrologic model. The average base flows for the stream network was provided by the Louisville District and was assumed constant for both flow models. The base flows were necessary to establish normal flow conditions. The base flow data was provided in cubic feet per second and was converted to cubic meters per second for use in both models.

Table 3-1. Base flows for the flow model stream network.

Stream	**ft^3/s**	**m^3/s**
Mill Creek	200	5.663
East Fork	40	1.133

The Hydrologic flow data was extracted from Andrysiak's HEC HMS model using precipitation data from a 25-yr storm event that occurred in April 1998. Since the HEC HMS model results were in a DSS format, the data could not easily be imported into the MIKE 11 interface. To make the data MIKE 11 readable, the runoff data derived from each drainage basin in the hydrologic model was converted into an *Adobe Acrobat* file (.pdf file) using *Adobe Distiller*. The runoff data was copied and pasted into a MIKE 11 time-series file and identified by each drainage basin identification number.

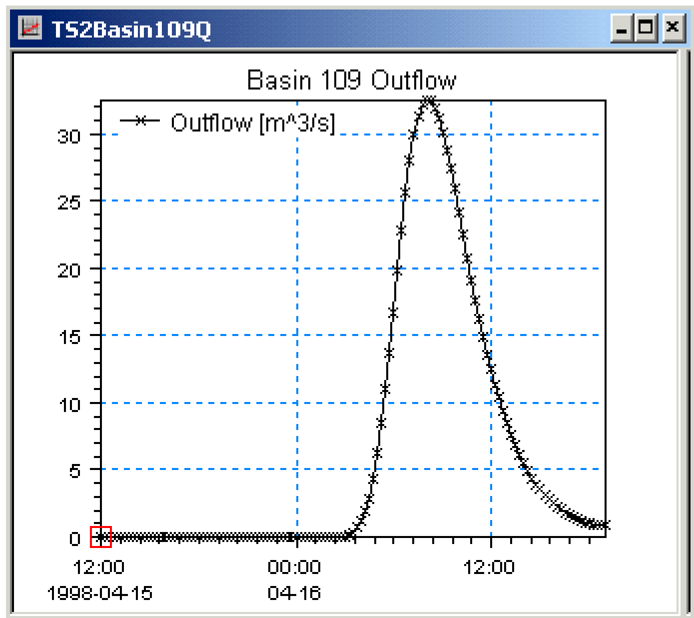


Figure 3-11. Runoff hydrograph for the Mill Creek Watershed's Basin 109.

Each watershed outlet was referenced to a location along the stream network. Thus, each runoff hydrograph was incorporated as lateral inflow into the stream network for both flow models. Accumulation of all the runoff data over a specified time range simulated the flood event for the model.

For drainage basins not directly connected to the river network, runoff hydrographs were accumulated for corresponding drainage basins for connectivity purposes. The accumulated runoff data existed in the HEC HMS model as flow at *junctions*. The runoff hydrographs computed from the HEC HMS model are provided in Appendix E.

Chapter 4: Modeling Methods

This chapter describes the modeling methodologies and capabilities of the computer software used in this study. The description discusses the hydraulic models, MIKE 11 and HEC RAS, and the hydrologic model, HEC HMS. The GIS-based applications, MIKE 11 GIS and HEC GeoRAS, which correspond to the MIKE 11 and HEC RAS models, respectively, are also discussed. Chapters 5 through 7 document the application of the computer models presented in this chapter using the data described in Chapter 3.

4.1 The MIKE 11 Model

The MIKE 11 hydrodynamic model was created by DHI in 1987. It is one of the most widely applied 1-D dynamic modeling tools for rivers and channels (DHI, 1999). Along with the MIKE 11 GIS extension to MIKE 11 GIS, time-series results from the MIKE 11 model can be imported into a GIS spatial environment for 2-D and 3-D flood visualization.

4.1.1 The MIKE 11 Hydrodynamic Model

The MIKE 11 model runs from a windows-based interface called *MIKE Zero*. To develop a MIKE 11 hydrodynamic model, five files are necessary: a *River Network* file, a *Cross-section* file, a *Boundary* file, a *Hydrodynamic Parameter* file, and a *Simulation* file. Implementation of the MIKE 11 model used in this study is discussed in Chapter 6.

In additional to the previously mentioned files, the hydrodynamic model can be expanded to model *Water Quality (advection and dispersion modeling), Sediment Transport*, and *Eutrophication*. MIKE 11 can also incorporate a *Flood Forecasting* file designed to perform calculations required to predict the variation in water levels and discharges in streams as a result of the Rainfall-Runoff hydrologic model implemented through the hydraulic model's boundaries. The Water Quality, Sediment Transport, Eutrophication, and Flood Forecasting options were not used in this study. Hydrologic modeling results were incorporated into the hydrodynamic model as lateral inflows in the Boundary file.

4.1.1.1 The Simulation file

The *Simulation* file acts as a "simulation manager" for the other files and does not require any external data. It defines the model type under the *Model* tab. By defining all the input files of the model under the *Input* tab, it acts as the link between the Network file and the other MIKE 11 files.

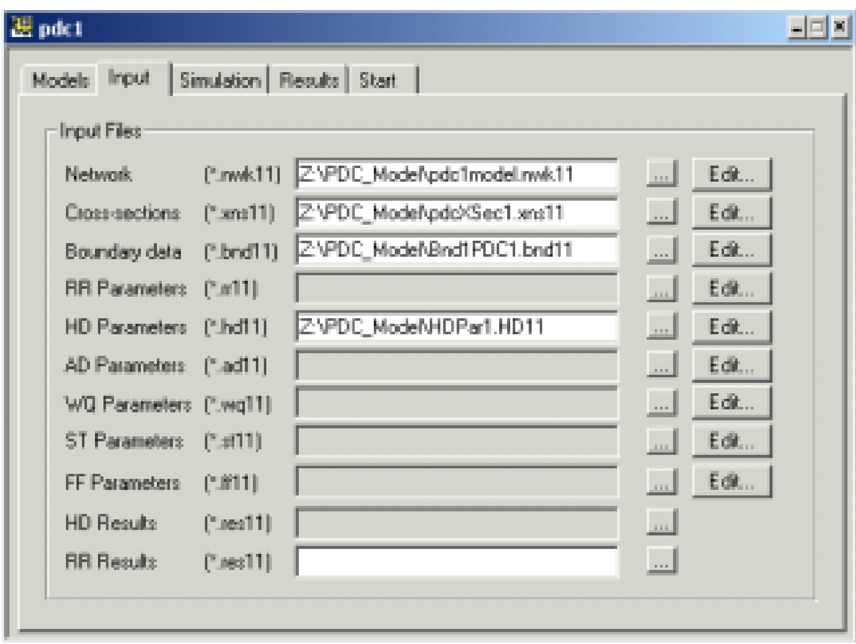


Figure 4-1. Input tab in a MIKE 11 Simulation File.

The *Simulation* tab contains the simulation and computation control parameters. The modeler defines simulation start and end times and time step under this tab. Under the *Initial Conditions* on the Simulation tab, the user establishes the initial conditions for the simulation. Options are *Steady State*, *Parameter file*, *Hotstart*, or *Steady and Parameter*. In the case of this study, the initial conditions were established using a *hotstart* file, as shown in Figure 4-2. A *hotstart* is a file that establishes base flow conditions for unsteady flow. The *hotstart* simulation is the steady-state solution for an unsteady flow model, which eliminates instability in the simulation created by initial conditions.

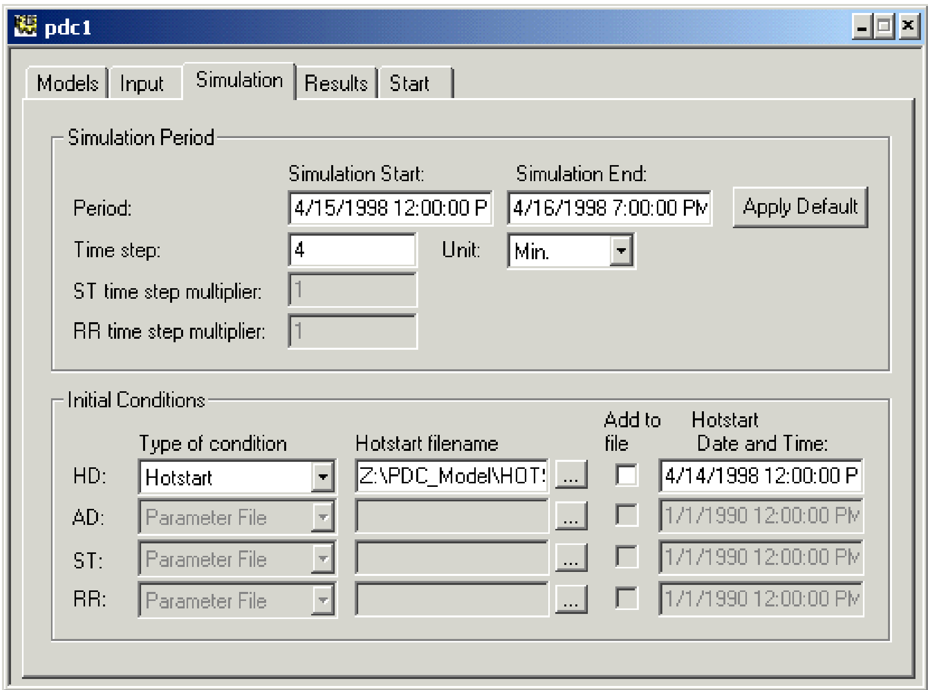


Figure 4-2. Simulation file with a “Hotstart” Initial Conditions Type.

The Simulation file also allows the modeler to determine the name of the results file. Once all information is inputted into the file, the Simulation file identifies any errors with the established conditions before running a simulation, as well as running an unsteady flow simulation.

4.1.1.2 The River Network File

The MIKE 11 model’s *River Network* file is the common link to the various

MIKE 11 files. It also has an XY coordinate system, allowing the model to import and export data to and from a GIS environment using the MIKE 11 GIS extension. The River Network file allows the modeler to 1) define the river network and reference cross-sections and control structures to the network; and 2) graphically obtains an overview of model information in the current simulation.

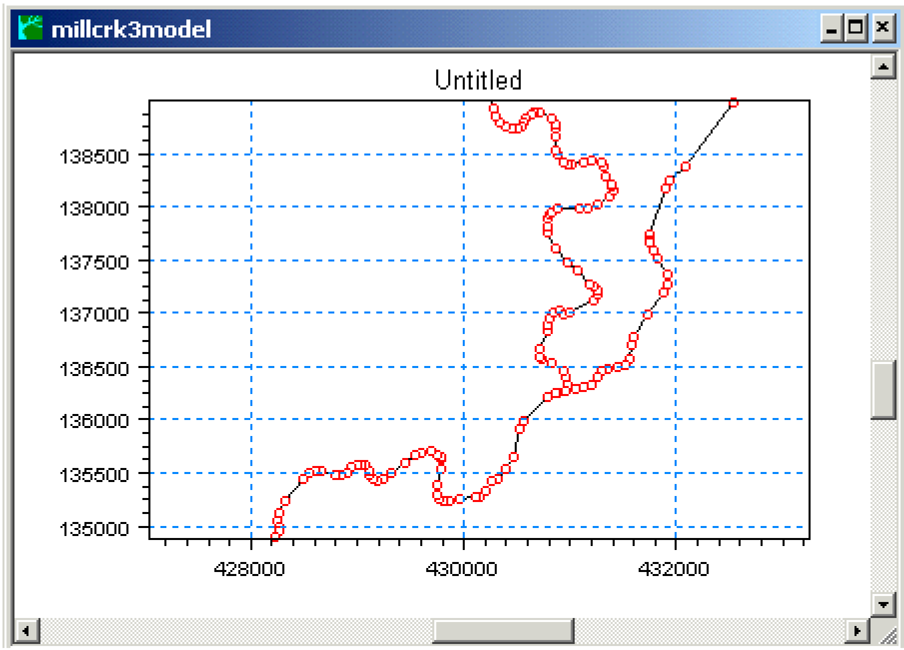


Figure 4-3. River network file defined by XY coordinate data points.

The River Network file can be digitized graphically, or inputted as XY coordinate data points, which are then manually connected. Chainage values along the network are automatically determined once the user defines the most upstream Chainage value(s). Control structures like dams, culverts, and weirs are added to the model in the River Network file, where the Chainage value referencing already exists.

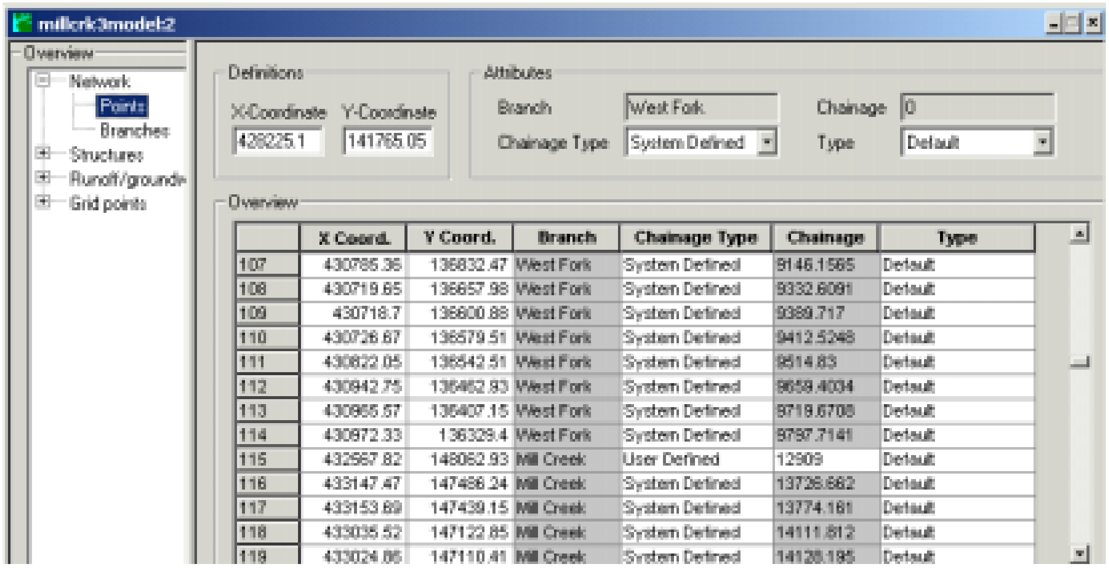


Figure 4-4. Tabular view of a river network depicting XY coordinate data points.

4.1.1.3 The Cross-section File

The *Cross-section* file contains streambed cross-sections as specified locations along the river network. The geometry of cross-sections usually is obtained from one of two sources - field-surveyed data or extracted from user-defined locations in a terrain model.

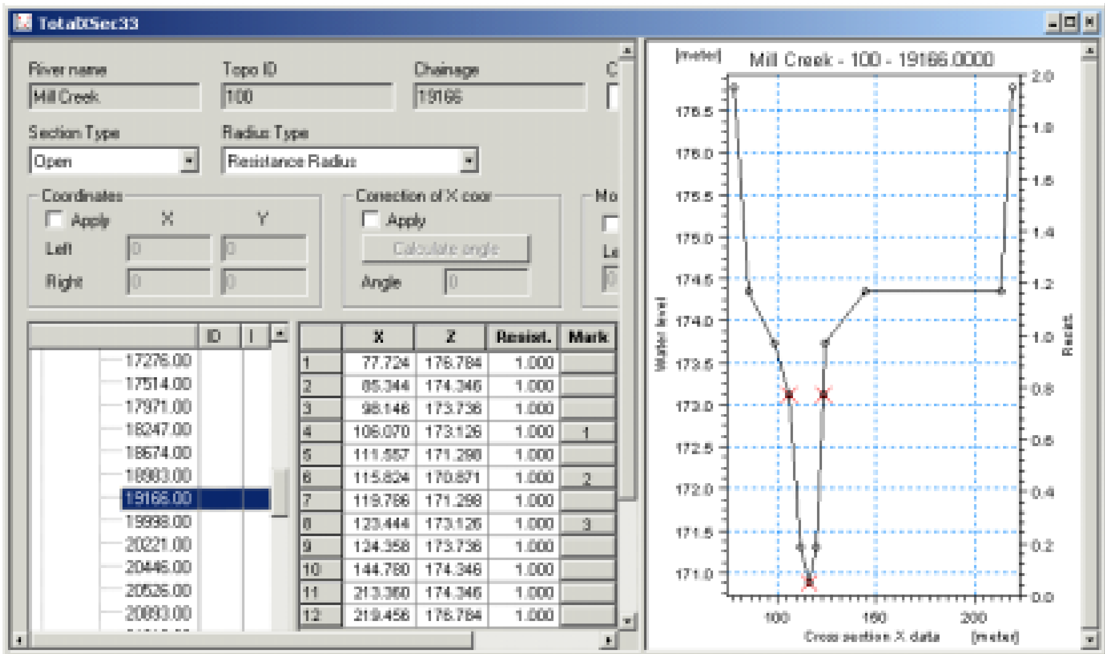


Figure 4-5. Raw data view of a cross-section in MIKE 11.

There are two types of cross-section data in MIKE 11: the *raw* data, and the *processed* data. The raw data is the geometric data of each cross-section derived from the above-mentioned sources. It also includes the local variation in bed resistance specific to that cross-section. The processed data is derived from the raw data and contains the cross-section's computational information used by the computer model. Cross-section raw data can be imported as a readable text file and can be edited directly from the Cross-section file editor.

4.1.1.4 The Boundary File

The *Boundary* file consists of boundary conditions in time-series format for the river network's boundaries. The file consists of four boundary condition options: *Hydrodynamic*, *Advection Dispersion*, *Sediment Transport*, and *Rainfall Runoff*. The Hydrodynamic option is the only boundary condition option used in this study.

Boundary types include *Water level* (h), *Discharge* (Q), *Q/h Relation*, *Wind*

Field, *Dambreak*, and *Resistance Factor*. The Water level boundary must be applied to either the upstream or downstream boundary condition in the model. The Discharge boundary can be applied to either the upstream or downstream boundary condition, and can also be applied to side tributary flow (lateral inflow). The lateral inflow is used to depict runoff for this study. The Q/h Relation boundary can only be applied to the downstream boundary.

The Wind Field boundary accounts for wind effects and can be applied globally or at specific branches in the river network. The Dambreak boundary simulates a dam's failure on the river network. The Resistance Factor boundary accounts for a time varying bed resistance along the river network. Only hydrodynamic boundary conditions were applied to this research.

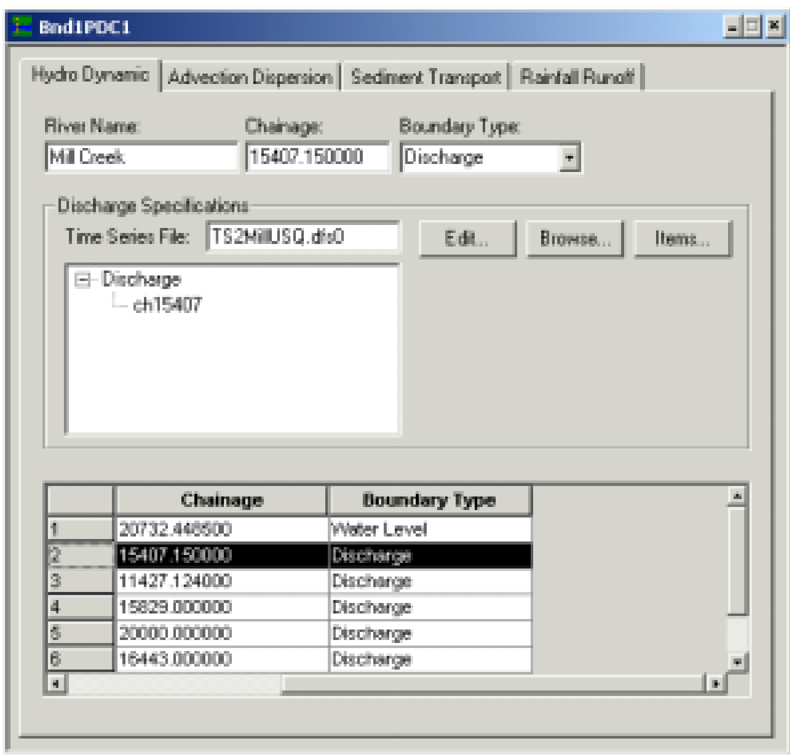


Figure 4-6. MIKE 11 boundary file.

Boundary types are linked to a time-series data file in the Boundary file. As shown in Figure 4-6, the boundary at Chainage value 15407.15 is defined as a *Discharge* boundary and is linked to a *Time Series File* under the *Discharge Specifications*.

4.1.1.5 The Hydrodynamic Parameter File

The *Hydrodynamic Parameter* file requires bed and flood plain resistance data for the river network. Differentiation between the streambed and flood plain along the river network is accomplished at each cross-section in the Cross-section file. Bed and flood plain resistance can be inputted as Chezy's *C*, Manning's *M*, or Manning's *n* values. The resistance factors are inputted from one location to another along the river network (chainage to chainage), as resistance changes. Resistance for streambeds and flood plains is inputted separately. Any local differences in resistance may be incorporated into the Cross-section file at a specified cross-section. The overall resistance is then the product of the resistance factor from the Cross-section file and the Hydrodynamic Parameter file at that specified location.

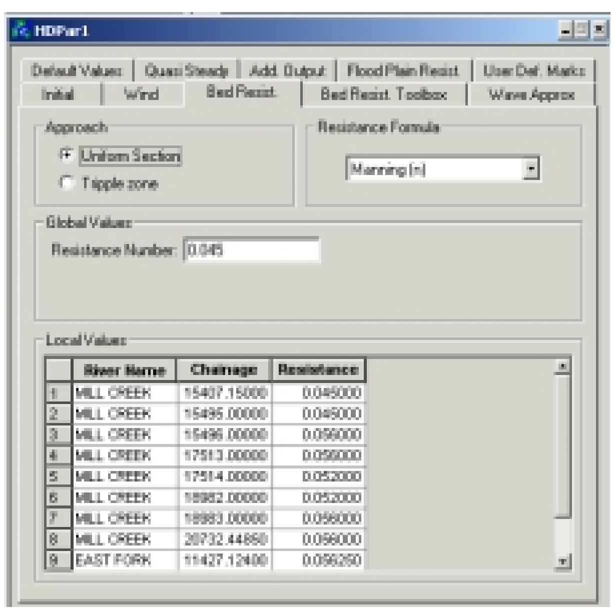


Figure 4-7. Bed resistance from chainage to chainage in the hydrodynamic file.

4.1.2 MIKE View

Results of MIKE 11 simulations can be observed using the MIKE View software. MIKE View displays longitudinal profile animations of both stage height and discharge resulting for a MIKE 11 model. It also can display stage height at any given cross-section, as well as provide rating curves at a specified location along the network.

MIKE View can also provide time-series results of stage heights at cross-section locations and time-series results of discharge at midpoints between two cross-section locations. This tool has been beneficial for this research by providing a facility for creating new boundary conditions for the model, as the study area was refined from the entire extent of the Mill Creek reach to a smaller area defined as the Primary Damage Center. To incorporate the contour data into the model, limitations to computer capacity had to be accounted for by refining the model area. The refinement focused on the most critical location of flood damage in the Mill Creek Watershed. Thus, the study area was refined to the Primary Damage Center.

4.1.3 The MIKE 11 GIS Extension

The MIKE 11 GIS extension integrates the MIKE 11 model with Arcview GIS. Like the MIKE 11 model, MIKE 11 GIS was developed by DHI. It acts as a bi-directional exchange between MIKE 11 and Arcview GIS. MIKE 11 GIS provides the following options to the modeler:

- Terrain model development in Arcview GIS using a grid-based mesh
- Extraction of geometric data from the terrain model for use in the MIKE 11 model
- Import MIKE 11 model time-series results into Arcview GIS for flood

visualization

- Develop 2-D and 3-D views and animations with the MIKE 11 model results and the corresponding terrain model (DHI, 1998)

If the river network in the MIKE 11 model already has a corresponding XY coordinate system to the terrain model, extraction of geometry data using MIKE 11 GIS is not required to import MIKE 11 results into Arcview GIS. If this is the case, the modeler needs to be aware of the differing data sources and ensure the existing geometry data is accurately geo-referenced with the river network.

4.2 The HEC RAS Model

HEC RAS is a hydraulic model created by the Hydrologic Engineering Center. The first version of HEC RAS was developed in 1990 and evolved from a steady flow model called HEC-2, first developed in 1966 (HEC-RAS, 1998). As computer capabilities improved, the HEC-2 software was converted to the windows-based HEC RAS software to better assist hydraulic modeling with a graphical user interface. In April 2000, the Hydrologic Engineering Center also developed the *HEC GeoRAS* extension of Arcview GIS, a pre- and post-processing tool for the HEC RAS model. HEC GeoRAS is an upgrade to the previously used AvRAS extension.

4.2.1 The HEC RAS Unsteady Flow Model

The HEC RAS model was initially used for calculating water surface profiles for 1-D steady-state flow. The results from the model have been applied to flood management and flood insurance studies throughout the United States. Recently, HEC RAS has incorporated an unsteady flow model in its beta version 3.0 (the final 3.0 version should be available by the end of calendar year 2000). The HEC RAS 3.0 version provides the modeler with an option to use either the steady flow or unsteady flow option. The unsteady flow option runs the UNET algorithm from the software. Results from the UNET algorithm are then imported back into HEC RAS for viewing of simulations.

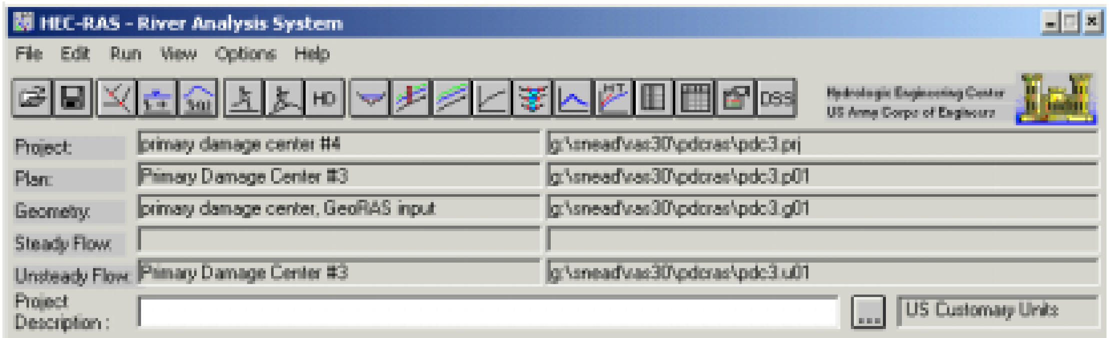


Figure 4-8. Main menu of HEC RAS version 3.0, with the unsteady flow option.

Along with the unsteady and steady flow options, the HEC RAS model also provides the following capabilities:

- Modeling of open channel networks and single rivers (both unsteady and steady flow options)
- Analysis of bridges, weirs, and culverts (unsteady and steady flow options)
- Modeling storage areas, navigation dams, tunnels, pumping stations, and levee failures (unsteady flow option only)
- Handling of subcritical, supercritical, and mixed-flow regimes (steady flow option only) (HEC-RAS, 1998)

The unsteady flow option was used for this project. To develop an unsteady flow model, three files are required: the *Geometric Data* file, the *Unsteady Flow Data* file, and the *Unsteady Flow Analysis* file.

4.2.1.1 The Geometric Data File

The Geometric Data File contains all the pertinent geometry necessary for hydraulic modeling. It establishes the connectivity of the river network (using River

Stations for network referencing), cross-section data (to include Manning's *n* resistance factors), stream junctions, and hydraulic structures. The file editor allows the importing of geometric data from previous HEC RAS versions, UNET models, and from Arcview GIS. Editing any of the geometric features can also be accomplished from this file.

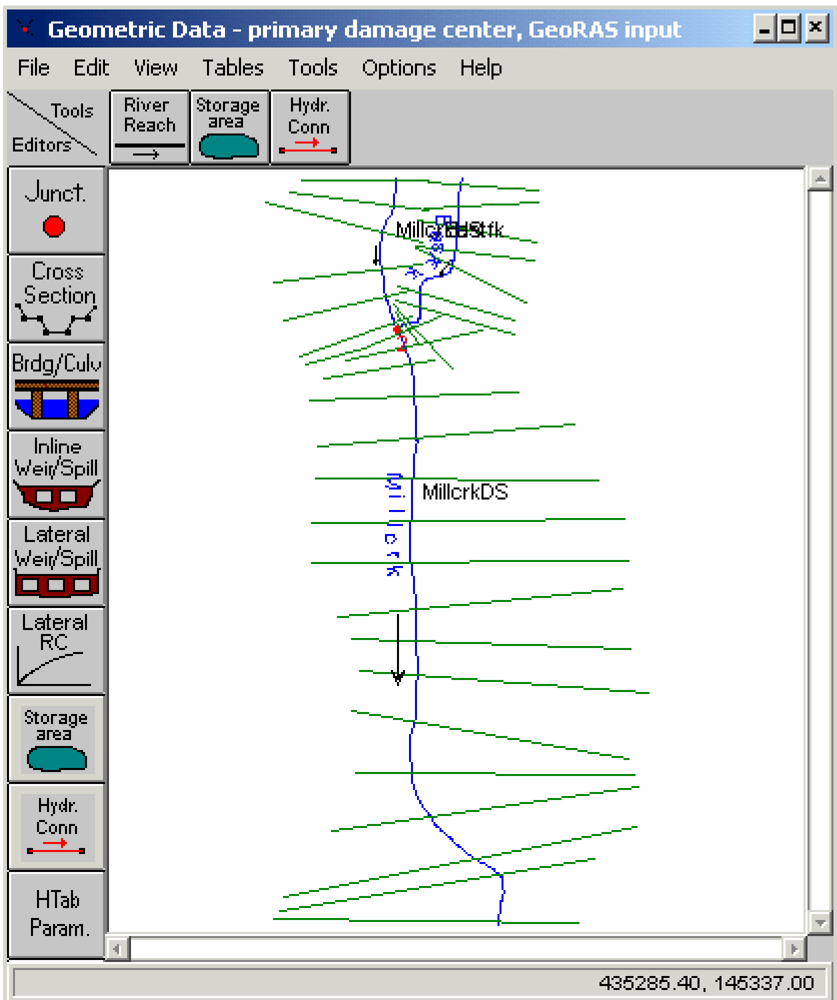


Figure 4-9. HEC RAS version 3.0 geometric data file editor.

HEC RAS version 3.0 also includes a *Storage Area* editor, a *Hydraulic Connectivity* editor, and *HTAB Parameters* editor. The Storage Area editor provides the modeler the capability to add and edit storage areas within the river network system. The Hydraulic Connectivity editor connects the river network and cross-sections with existing hydraulic structures and storage areas. The HTAB Parameters editor establishes the initial conditions for the unsteady flow option (initial water surface elevation at each cross-section in the network) and the incremental unit value (for the change in water surface elevations) used in the UNET algorithm. The incremental unit value is the incremental change of water surface elevation used by the UNET algorithm, and is set to a default of 0.1 meters.

4.2.1.2 The Unsteady Flow Data File

The Unsteady Flow Data file consists of the boundary conditions and initial conditions for the model. The initial conditions contain the initial flow distribution for each reach within the river network. The time-series boundary conditions contain the upstream and downstream boundary conditions (at a minimum) defined as a *Stage*, *Flow*, or *Stage and Flow* hydrograph. Internal river network boundary condition options include *Lateral Inflow*, *Uniform Lateral Inflow*, and *Groundwater Interflow* hydrographs. The Lateral Inflow hydrograph option depicts tributary, point source, or watershed outlet (runoff) inflows. The uniform lateral inflow depicts overland inflow evenly distributed from one River Station location to another along the river network. Lastly, the Groundwater interflow hydrograph models inflow into the river network from groundwater recharge.

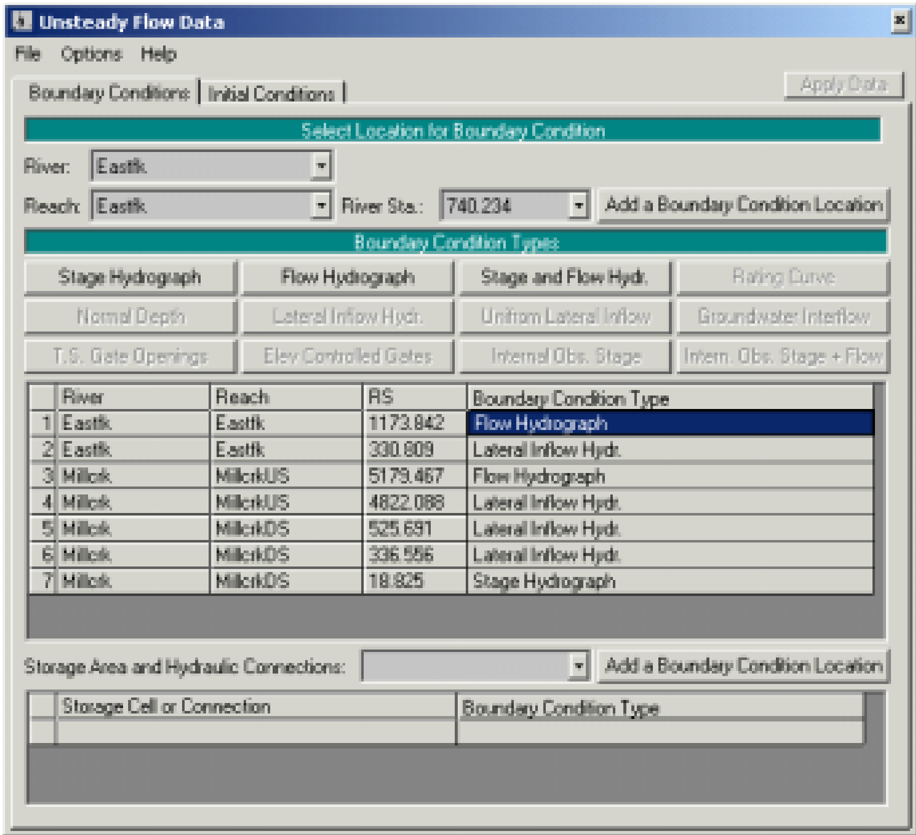


Figure 4-10. HEC RAS version 3.0 unsteady flow data file editor.

Once the boundary and initial conditions are defined in the Unsteady Flow Data File editor, each boundary condition is linked to a user inputted time-series data editor. The time-series data can be linked to a HEC HMS or HEC RAS model results using the DSS interchange or inputted manually into the time-series data chart. The modeler also defines the time-series data's time interval and reference starting time from this editor.

4.2.1.3 The Unsteady Flow Analysis File

The Unsteady Flow Analysis file establishes the user specified conditions for the unsteady flow simulation. The modeler sets the starting and ending time for the simulation, and establishes the computational settings for running the UNET algorithm. The computational settings include the computational interval, hydrograph output interval, and instantaneous profile interval. The instantaneous profile interval must be equal to or greater than the computational interval to run the simulation.

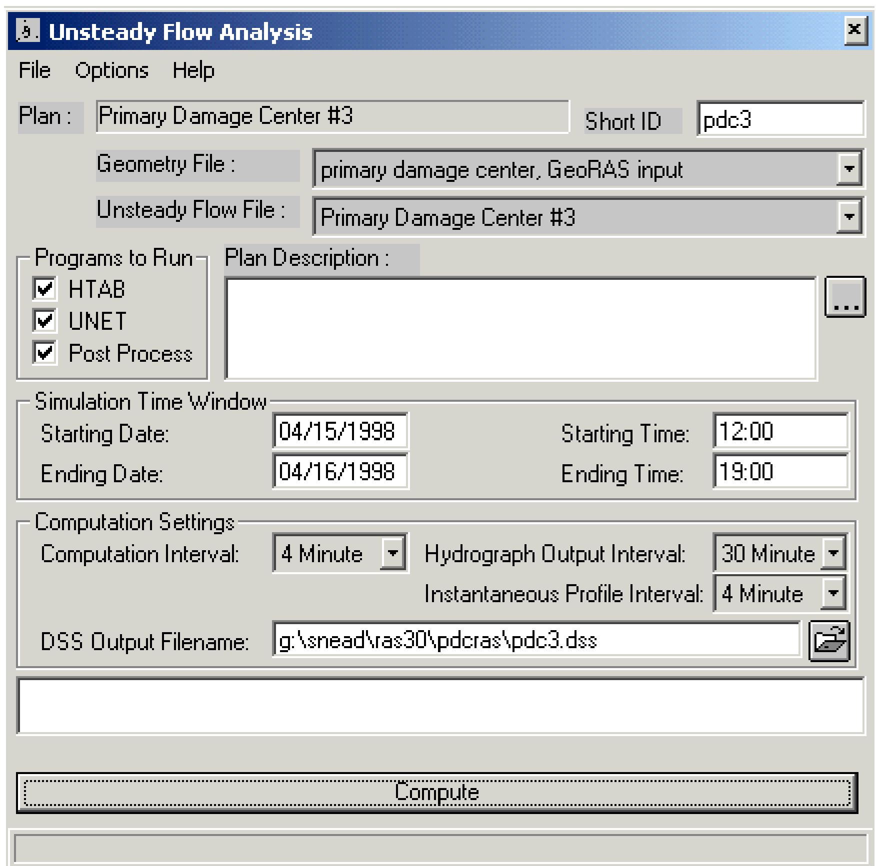


Figure 4-11. HEC RAS version 3.0 unsteady flow analysis file editor.

Once the unsteady flow model is simulated, errors in logic for the geometric, HTAB, and unsteady flow data are identified by the software. Once all errors have been resolved, the HEC RAS software runs an HTAB algorithm to establish the initial conditions for the entire river network, in preparation for running the UNET algorithm. Once that is accomplished, the computer executes the UNET algorithm for the simulation. Results include water surface profiles for each cross-section at each time step within the starting and ending time ranges for the entire river network.

4.2.2 The HEC GeoRAS Extension

The HEC GeoRAS extension integrates results from the HEC RAS model into Arcview GIS. It acts as a geometric data pre-processor and HEC RAS results data post-processor in Arcview GIS. HEC GeoRAS provides the following options to the modeler:

- Extraction of geometric data from a TIN-based terrain model for use in the HEC RAS model (pre-processing)
- Import of the HEC RAS model time-series results into Arcview GIS for flood visualization (post-processing)

Unlike the MIKE 11 model, geometric data must be extracted from the terrain model into the HEC RAS model to develop flood visualization in Arcview GIS. This pre-processing step geo-references the unsteady flow model results to the terrain model. The GeoRAS extension also develops a bounding polygon in Arcview GIS, which establishes the limits of flooding in the terrain model. If the modeler is unaware of floodplain extents prior to developing the model, the bounding polygon may be too wide or too narrow when observing the HEC RAS results in Arcview GIS using the post-processor. By iteration, the optimum size of the bounding polygon can be determined.

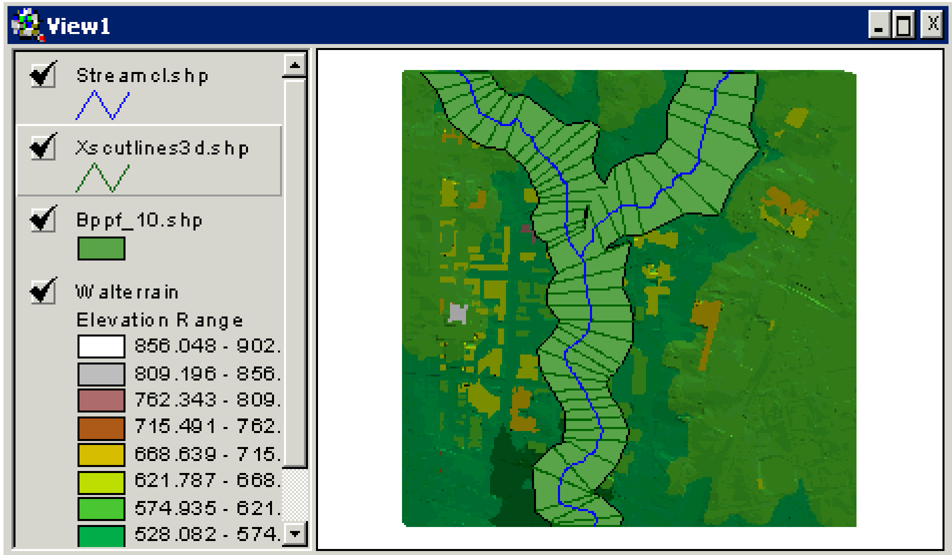


Figure 4-12. Bounding polygon derived from cross-sections using GeoRAS. The terrain model is of Waller Creek flowing through the University of Texas Main Campus.

4.3 The HEC HMS Model

HEC HMS is a hydrologic model developed by the Hydrologic Engineering Center of the U.S. Army Corps of Engineers. In 1968, HEC released the HEC-1 computer model to aid engineers in hydrologic analysis. The windows-based HEC HMS software was released in 1998. The program simulates a rainfall runoff response of a watershed system to a precipitation input by representing the entire watershed as an interconnected system of hydrologic and hydraulic components, which include watersheds, streams, and reservoirs. The results from a HEC HMS model can be used as input data for hydraulic modeling.

The HEC HMS software provides the following computational options to deriving runoff responses to simulate precipitation-runoff processes:

- Several alternatives for loss determination
- Lumped or linearly distributed runoff transformation methods
- Routing options

- An optimization system for calibration (HEC-HMS 1998)

4.3.1 Loss Determinations

The term "losses" refers to the amount of the rainfall from a storm event that is diverted from runoff, usually infiltrating to soil or flowing to other means of storage in the watershed system. The HEC HMS model supports the most common methods for calculating losses, like the *initial/constant* rates, *Soil Conservation Services (SCS) Curve Number* method, and the *Green and Ampt* method. These methods can be lumped or linearly distributed throughout the model. In a lumped analysis, losses are spatially averaged over a watershed within the watershed system. For a linearly distributed method, the rainfall is spatially defined for the entire watershed system, and losses are averaged for each watershed in the system.

4.3.2 Runoff Transformations

Runoff transformations convert the precipitation from a storm event, minus the losses, to direct runoff for each watershed in the system. The runoff is computed as a hydrograph response at each watershed's outlet. Like the loss determination, the HEC HMS software allows the modeler to use lumped or linearly distributed approaches to runoff transformation. In a lumped analysis, the amount of runoff is determined either using unit hydrographs like the *Clark*, *Snyder*, or *SCS* hydrographs, or the *kinematic wave* method. In a linearly distributed method, like the *Modified Clark* hydrograph, the watersheds in the watershed system are spatially interpreted as numerous grid cells within a user-defined grid mesh, and the time (known as lag time) for excess rainfall to move from that grid cell to the watershed's outlet is determined. The hydrograph for the Modified Clark method is created from the sum of the all the grid cell's lag times for each watershed in the system.

4.3.3 Routing

Routing is the movement of the runoff from the different watershed outlets throughout the system along the streambed, and ultimately to the outlet or sink of the entire watershed system. The HEC HMS model routing options include the *Muskingum*, *Modified Puls*, *Kinematic Wa*ve, and *Muskingum-Cunge* methods.

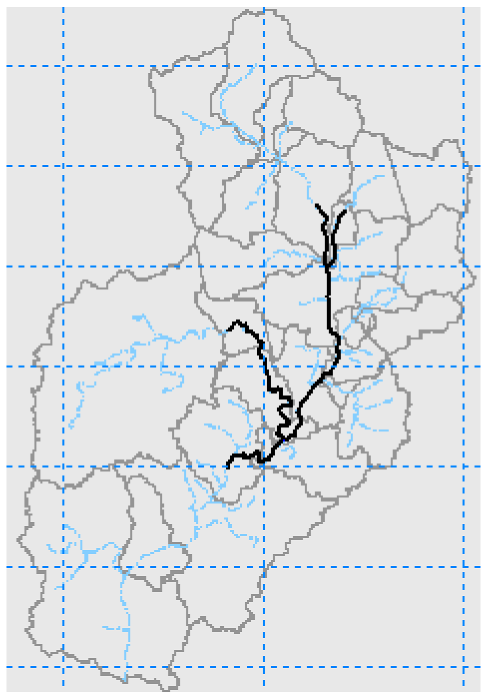


Figure 4-13. Discontinuities between watersheds in a hydrologic model and the boundaries of the hydraulic model (shown in bold).

Hydraulic models do not always model the entire stream network used in a corresponding hydrologic model, as shown in Figure 4-13. Some modelers may further refine the study area to a smaller range. In such cases, the routing methods provided in HEC HMS software can provide flow hydrographs at locations known as junctions along the stream network as well. This provision can compensate for discontinuities between the two models by providing upstream and downstream boundary conditions for the further refined hydraulic model.

4.3.4 Parameter Optimization

To use the HEC HMS model as an engineering modeling tool, it requires calibration to the historic flow conditions of the actual watershed system. The process can be simple or complex and requires the adjustment of numerous parameters to optimize model results. The HEC HMS software provides an option for model optimization.

The HEC HMS model used for this study was not calibrated, because of a number of complications existing in the actual watershed system. Combined sewer overflows, the unknown capacity for storage, and the diurnal effects of wastewaters all contribute to the on-going hydrologic problems with the Mill Creek Watershed. More information on the hydrologic model and its calibration is discussed in further detail in Andrysiak's report.

Chapter 5: Terrain Model Development

When delineating floods in a spatial environment, the accuracy of the terrain model is very critical. The most accurate terrain data currently used is obtained from photogrammetry. Photogrammetry is the science or art of obtaining reliable measurements by means of photographs (Tate, 1998). One of the most common uses of photogrammetry is the analysis of aerial photography to extract ground elevations to produce topographic maps.

Digital terrain data is obtained from a plane traveling over a study area taking photographs. Photographs are taken from two passes of the study area, so that every point on the ground appears in at least two successive photographs. Digital terrain data, like a DEM or contour data, is obtained from the photographs using either an analog instrument called a stereoplotter, or by using digital image processing software (Tate, 1998). Photogrammetry data is limited to the many arbitrary surfaces that make up the terrain. So, if water exists in a streambed when the photographs are taken, the water surface elevation data (not the streambed's geometry data) is included as part of the terrain data.

In such cases, hydraulic modelers find themselves in a quandary – how can one integrate accurate terrain data with existing streambed geometry (i.e. surveyed data of the streambed) to delineate flood events? As previously discussed, Tate created a terrain model from surveyed flood plain data and a DEM. Azagra-Camino developed a terrain model from accurate photogrammetry data, but did not compensate for water in the streambeds, making the streambed geometry inaccurate. For this study, both methods were examined to optimize the terrain model. Since the contour data was accurate to 2-ft for this study, using Tate's method to integrate the entire flood plain of the study area's hydraulic model into the terrain model was not the solution. Highly accurate contour data existed near the stream, like bridge embankments and levees. Using Tate's method may compromise the contour data. After numerous iterations and trials, the best option used for this study was to integrate only the streambed geometry, without the flood plain geometry, with the terrain model.

5.1 Methodology of Terrain Model Development

Using the contour data provided by the Louisville District, the three 1-ft contour themes were merged in Arcview GIS to account for the entire PDC study area. As previously discussed, the 1-ft merged contour theme was modified to a 2-ft contour theme by deleting every other contour line in the file. The new contour theme was created and saved as *pdc2ftcontrs.shp*.

No data was available for a small section on the west side of the study area (which was outside the extent of the flood plain). To compensate for this lack of data, point elevations were extracted from a 30-meter DEM. The section's missing data was clipped from the point elevations and saved as a point shape theme called *pdctmpts.shp*.

5.1.1 Initial Terrain Model Development

Using an algorithm known as *Delaunay Triangulation*, Arcview GIS optimizes a 3-D representation of the terrain by creating triangles that are as close to equilateral as possible. The result is a TIN-based terrain model. It is a terrain representation using points in three-dimensional space, with topological faces in two dimensions (*ESRI*, 1999).

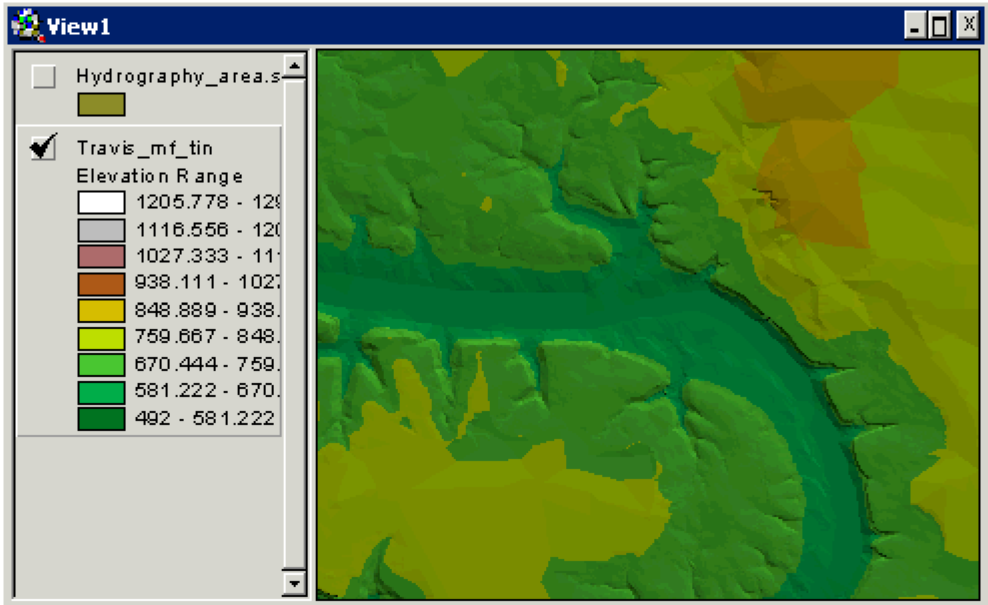


Figure 5-1. Example of a TIN-based terrain model. The TIN represents a portion of Lake Austin in Austin, TX, developed by Kevin Donnelly at the Center for Research in Water Resources.

Using the *3D Analyst* extension in Arcview GIS, the terrain elevation data was extracted from the *pdctmpts.shp* and *pdc2ftcontrs.shp* file to develop a TIN of the study area. A bounding polygon, called *theme1.shp*, was used to define the study area's boundaries, as shown in Figure 5-1. The point elevations were defined as *mass points* and the contour lines were defined as *soft breaklines* during the setup. Like mass points data, soft breaklines act as elevation input to the terrain model, but maintain continuous slope for the terrain's surface. The TIN was created using the *Create TIN from Features* command in Arcview GIS. The initial TIN-based terrain model was saved as *Crtin1*.

Figure 5-2. Points, contours, and bounding polygon used for the PDC terrain model.

5.1.2 Limitations of Digital Terrain Data used for Hydraulic Modeling

The digital terrain data did not contain an accurate geometric representation of the streambed for use in the unsteady flow models. To verify this, the geometric data of the streambed was extracted from the terrain model and imported into HEC RAS (this extraction was accomplished using HEC GeoRAS, and is explained further in Chapter 7). There were two problems with the digital terrain data that affected the overall hydraulics of the system. First, the digital terrain data streambed elevations are on average 2.25 meters higher along the length of Mill Creek when compared to the surveyed cross-section data, as shown for River Station 43982 in Figure 5-3. Thus, the photogrammetry data is accounting for water in the stream. The range of the elevation difference ranged from approximately 2.1 to 2.4 meters higher for the extracted terrain data than the surveyed data along Mill Creek's longitudinal profile. Figure 5-4 illustrates the difference in the two profiles. This is a difference of approximately 259,000 m^3 in water volume that the initial terrain model did not account for.

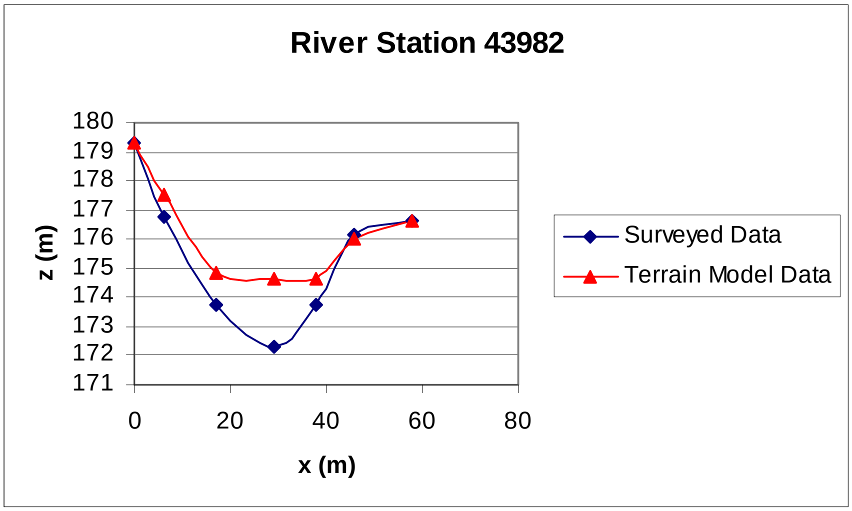


Figure 5-3. A surveyed cross-section of Mill Creek compared to terrain model data.

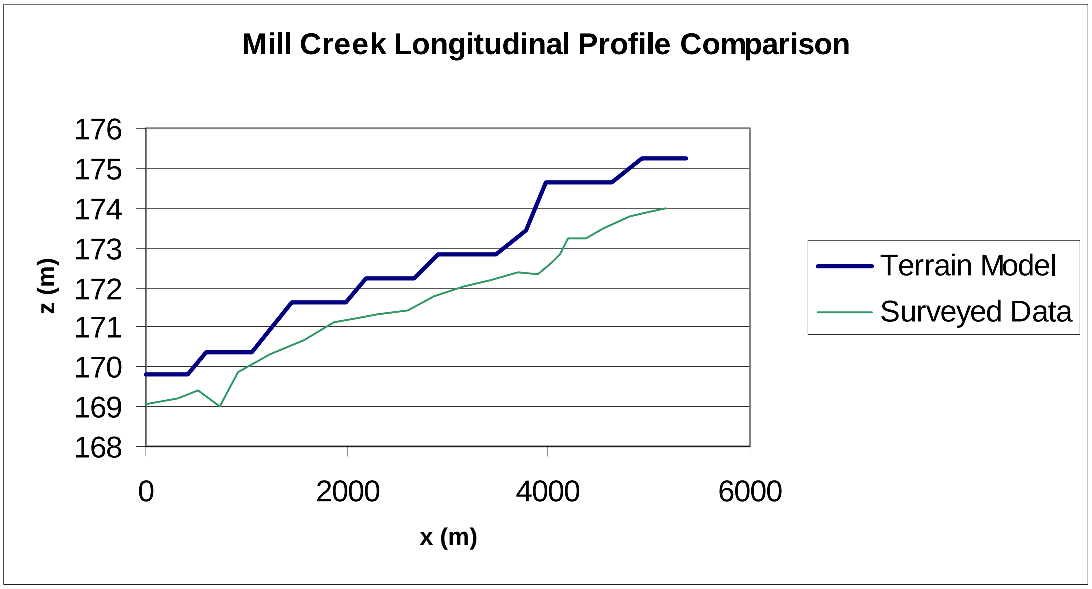


Figure 5-4. Comparison of the Mill Creek streambed's longitudinal profile developed from the terrain model and the HEC-2 surveyed data.

Secondly, the longitudinal axis of Mill Creek, as viewed in HEC RAS, depicted a terraced streambed, as shown in Figures 5-4 and 5-5. The axis did not accurately represent the streambed of Mill Creek. The natural effects from erosion and deposition create a much smoother transition from upstream to downstream. The terraced effect also created supercritical and subcritical flow regimes along the stream, which was difficult to represent in an unsteady flow model based on the initial assumption of subcritical flow. The terraced streambed was created from the interpolated TIN data. Using contour line data as the input, the interpolation was not linear, but instead developed plateaus at each contour line. This may have been the result from defining the contour lines as soft breaklines instead of hard breaklines.

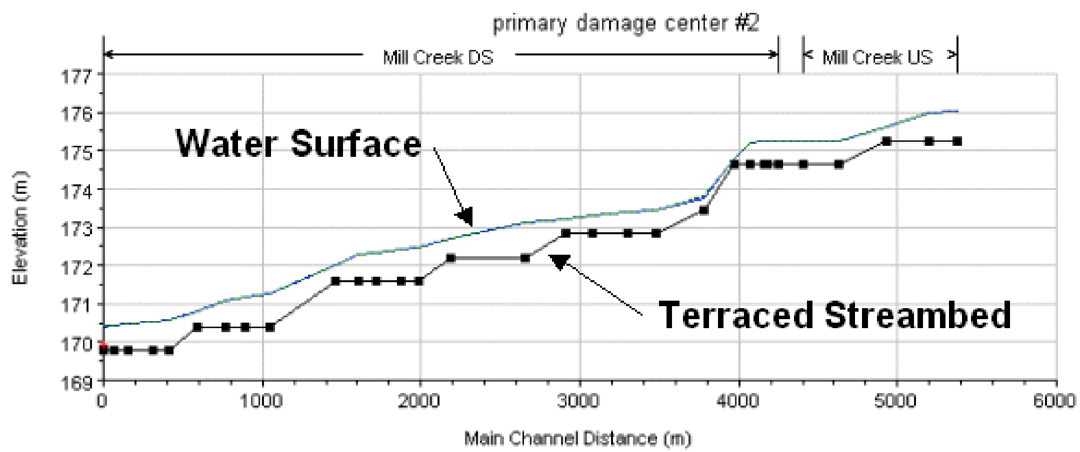


Figure 5-5. Terraced streambed of Mill Creek created from the TIN data.

5.1.3 Integration of Streambed Geometry and Terrain Data

To integrate the geometric attributes of the streambed with the digitial terrain data, a *Floodmap* utility developed by Tate (1999) was used. Tate created the utility for the purpose of incorporating HEC RAS geometry data into a terrain model for floodplain delineation. The utility produces a modified TIN-based terrain model by:

1) Importing stream cross-sectional data from HEC RAS into Arcview GIS
2) Geo-referencing the cross-sections to the corresponding location along the stream in the terrain model
3) Converting the stream geometry to 3-D themes in Arcview GIS
4) Adding the 3-D stream geometry to the existing digital terrain data

The floodmap utility first removes the spatial bounds defined by the digital terrain data before adding the 3-D stream geometry. Then the entire floodplain is incorporated into the terrain model. For this study, surveyed data of the streambed only was incorporated into the terrain model by modifying Tate's methodology.

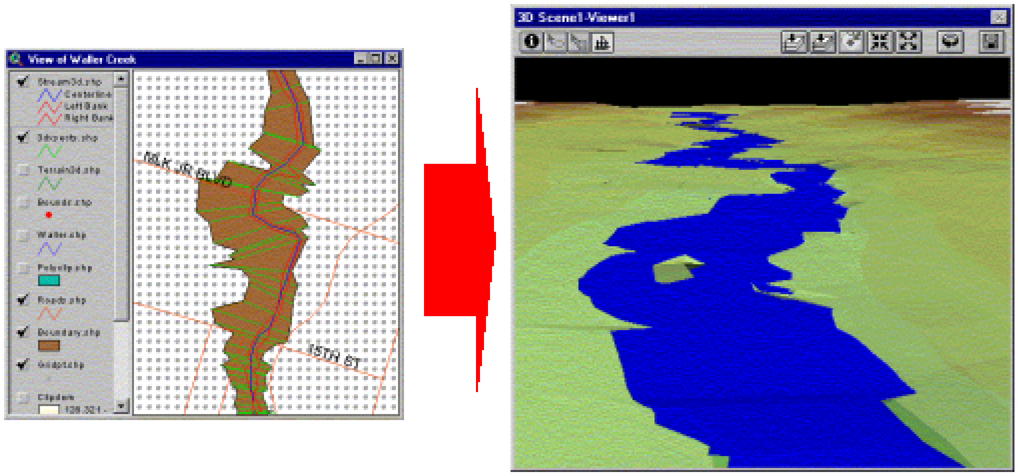


Figure 5-6. Tate’s Method of incorporating flood plains into a terrain model (Tate, 1999).

5.1.3.1 Importing Cross-sectional Surveyed Data into Arcview GIS

The floodmap utility was limited to defining the 3-D stream centerline and bank lines from the imported cross-section locations, as a straight line from cross-section to cross-section, as shown in Figure 5-7. If the number of cross-sections is limited and the cross-sections do not account for every bend in the stream, then the stream centerline location with respect to the terrain model will be inaccurate. By increasing the number of cross-sections along the stream centerline, the straight line segments derived by the floodmap utility would get smaller and smaller, creating a more accurate depiction of curves in the stream for the model. More cross-sections were required, especially along curved sections of the stream centerline. To compensate for this, cross-sections between surveyed cross-section data were interpolated in the HEC RAS model before being imported into Arcview GIS.

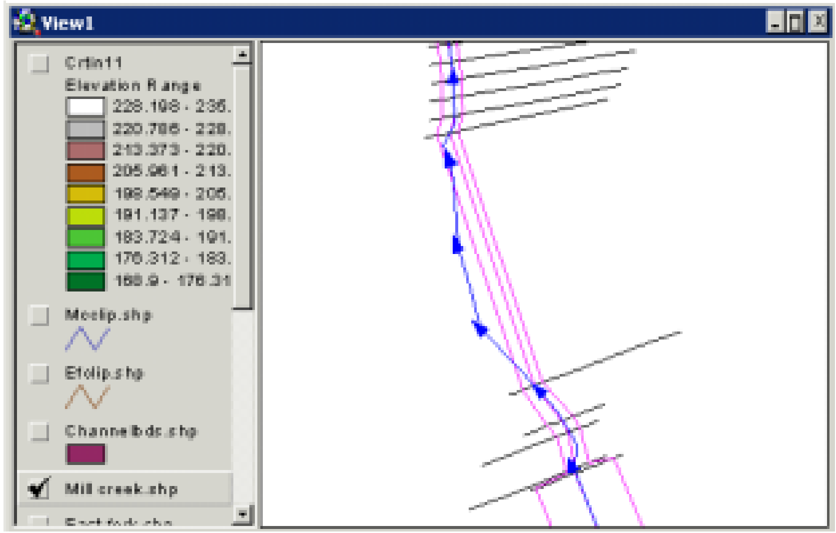


Figure 5-7. Comparison of the stream (blue arrows) and a 3-D stream centerline and bank lines created by the Arcview GIS *Floodmap* utility.

The development of interpolated cross-sections between the surveyed cross-sections in HEC RAS when defining the stream centerline and bank lines was an iterative process. Imported data were compared to the actual stream centerline in Arcview GIS for accuracy. If they did not match, then additional cross-sections were interpolated until the derived stream centerline overlapped the actual stream centerline. Spacing between interpolated cross-sections was typically around 25 meters in stream centerline length.

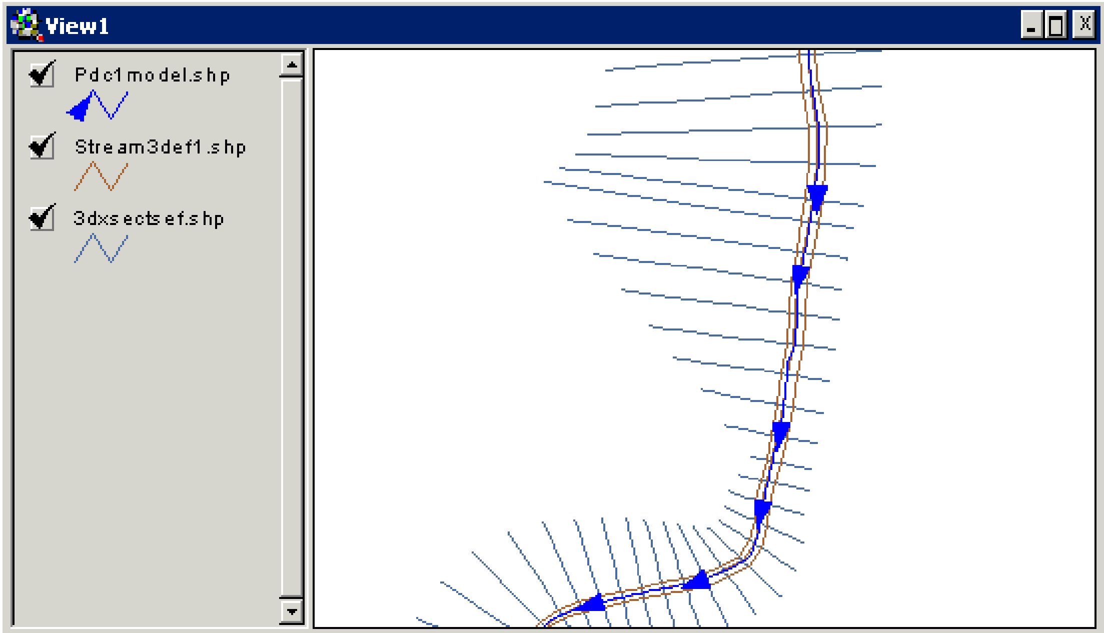


Figure 5-8. A revised depiction of cross-sections and bank lines as compared to the stream centerline (shown with blue arrows). A significant improvement is apparent when compared to the non-interpolated cross-sections shown in Figure 5-7.

Figure 5-8 shows the addition of the interpolated cross-sections to the surveyed cross-section data. This method decreased straight line distances between cross-sections using the floodmap utility, thus improving the depiction of curvature for the stream centerline. A significant improvement is noticed when comparing the stream bed depiction to the stream centerline shown in Figure 5-8 to the previous depiction in Figure 5-7.

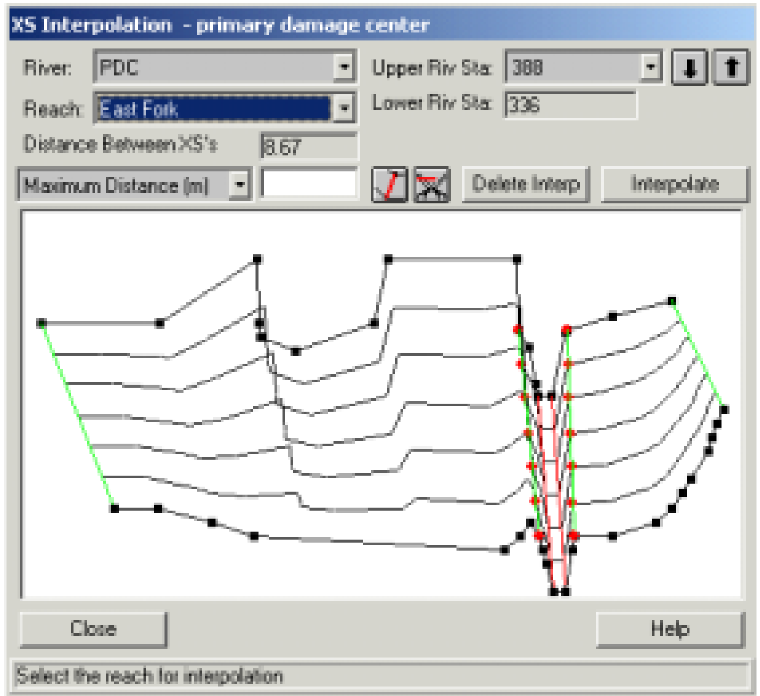


Figure 5-9. Cross-sections interpolated between existing cross-sections in HEC RAS.

Once the interpolated cross-sections were finally developed, the data was exported into Arcview GIS by using the *Generate Report* command in HEC RAS. Tate's Floodmap utility creates a text file in dBASE format from the HEC RAS report. The text file includes River Station identification numbers, water elevation (for steady-state profiles in HEC RAS), lateral and elevation coordinates of all cross-section points (stored in a global variable, not in the table), the width of the left and right flood plains with respect to the stream centerline, the elevation of the left and right banks and stream centerline, and downstream reach lengths between cross-sections. Once the data was imported into Arcview GIS, the stream centerline was geo-referenced to the digital terrain data prior to incorporating the stream geometry into the terrain model.

5.1.3.2 Cross-section Geo-referencing

Locations along the stream network require accurate geo-referencing with the terrain data. It is possible that the digital stream centerline may have minor differences in length compared to the HEC RAS stream centerline. To compensate for these inconsistencies, the floodmap utility assigns upstream boundaries, downstream boundaries, and intermediate stream definition points along the stream. This is accomplished by assigning definition points at a cross-section located near a well-defined reference point in the terrain data, such as a bridge or culvert location. For this study, the corresponding road network, called *rd3dclp.shp*, was used to identify bridge locations along the stream network.

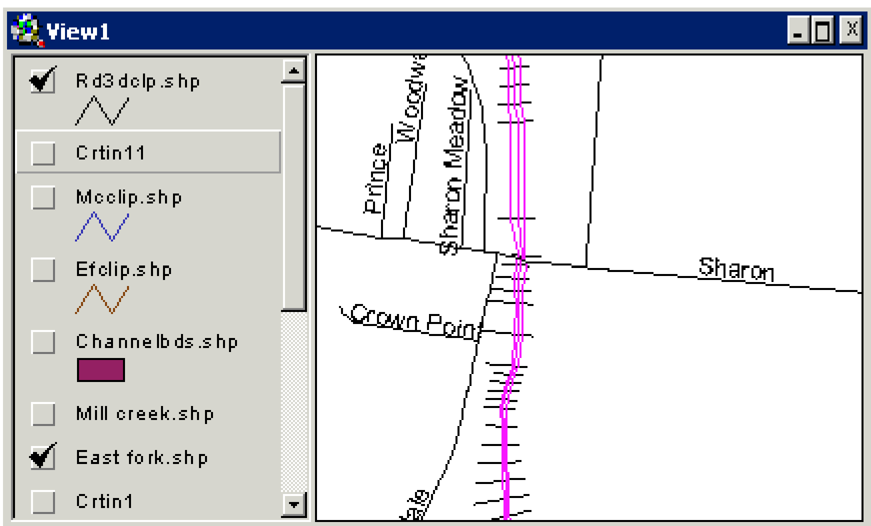


Figure 5-10. Sharon Rd. used as an intermediate point for geo-referencing.

For this study there are four intermediate points identified at the intersection of the roads and the stream centerline. The upstream boundary is defined as the Hamilton/Butler County line and the downstream boundary is defined as Glendale Road.

Table 5-1. Stream definition points for the study area.

Type of Point	Location	RS Number
Mill Creek		
Upstream Boundary	County Line	200055
Intermediate Point	Highway I-275	195540
Intermediate Point	Kemper Road	194227
Intermediate Point	Sharon Road	188635
Downstream Boundary	Glendale Road	182205
East Fork		
Upstream Boundary	County Line	388
Downstream Boundary	Confluence with Mill Creek	0.0

5.1.3.3 Converting Stream Geometry Data into 3-D Themes

The River Stations (RS) for the surveyed cross-sections that correspond with the stream definition points (as shown in Table 5-1) were labeled in the imported dBASE table. The geo-referencing process, as well as the subsequent 3-D theme development, is accomplished separately for Mill Creek and East Fork. The Floodmap utility creates a 3-D cross-section theme and a 3-D stream theme for the two streams in the study area using the *Mapping HEC RAS Cross-sections* command. The HEC RAS cross-section locations are geo-referenced to the terrain, defines the stream centerline and bank lines. The 3-D cross-section themes were saved as *3dxsectmc.shp* and *3dxsectef.shp*. The 3-D stream themes, consisting of a stream centerline and channel banks, were saved as *Stream3dmc1.shp* and *Stream3def1.shp*.

The 3-D themes created in this process are *polylineZ* files. PolylineZ files contain an elevation attribute to form a three-dimensional line, or arc. A 3-D depiction of the Mill Creek polylineZ files is shown in Figure 5-11. The next step in the process was to integrate the polylineZ themes into the terrain model.

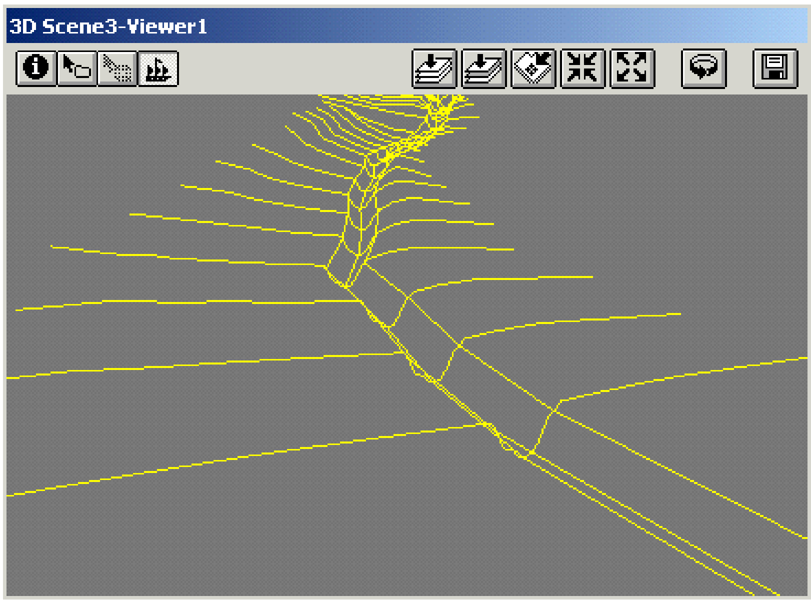


Figure 5-11. *PolylineZ* themes of the stream channel and cross-sections.

5.1.3.4 Incorporating Stream Geometry into the Terrain Model

Prior to integrating the stream geometry into the terrain model from the existing polylineZ themes, the terrain model was converted to a *mass point*s theme, with each point representing a point elevation. The purpose of the conversion was to create a depiction of the existing terrain model that can be edited in Arcview GIS. This was first accomplished by converting the existing terrain model, *Crtin1*, to a Grid-based model. By using the *3D Analysis* extension, the TIN-based model was converted to a Grid-based model using the *Convert to Grid* command. The grid mesh was defined by 5-meter by 5-meter grids. The Grid-based terrain model was saved as *Pdcgrid1*. The Grid-based terrain model was converted to mass points using the *Convert Grid to Points* command in the Floodmap utility. The mass points were saved as *Gridpts.shp*.

In Tate's method, a bounding polygon is developed from the 3-D cross-section themes, defining the extent of the flood plain. For this study, this step was modified. Instead of highlighting the 3-D cross section themes to define the bounding polygon, the 3-D stream themes were highlighted. This established the stream banks as the extent of the bounding polygon. The 3-D cross-sectional data was also limited to the stream channel as well, by clipping the Mill Creek and East Fork cross-section themes, saving them as *Mcclip.shp* and *Efclip.shp*. This process alleviated any overlap in the data, as shown in Figure 5-12, and then was used to develop a modified terrain model.

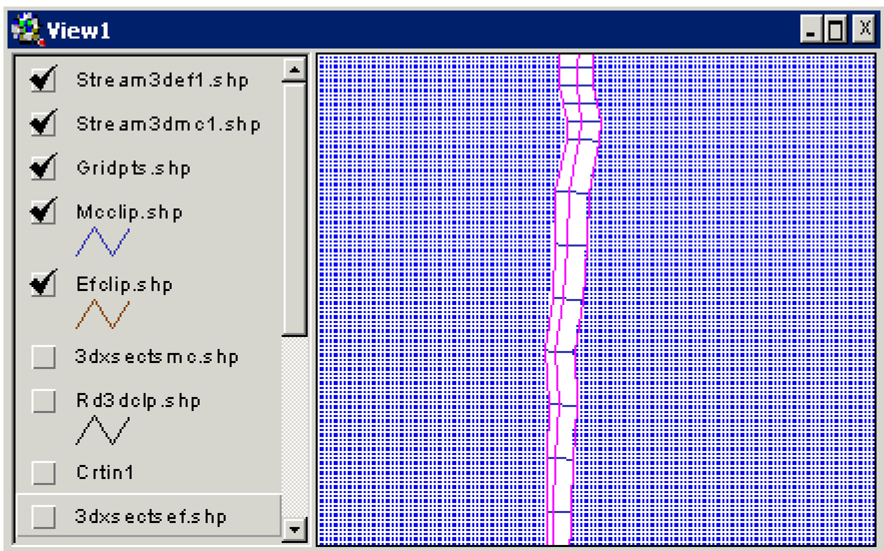


Figure 5-12. Section of Mill Creek with mass points data and stream geometry.

Defining *Gridpts.shp* as *mass points* and channel geometry as *hard breaklines*, a modified terrain model was developed, using the *Create TIN from Features* command from the *3D Analyst* extension. The developed TIN-based terrain model was saved as *Nwtin1*. Figure 5-13 shows the depiction of the modified terrain model, with the surveyed stream geometry.

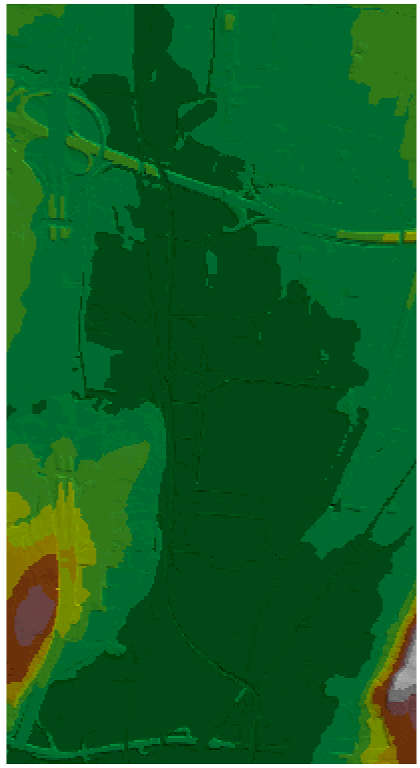


Figure 5-13. TIN-based terrain model modified with surveyed stream geometry.

The modified TIN-based terrain model was used with the HEC GeoRAS interface. Unlike the MIKE 11 model, stream geometry data were extracted from the terrain model for use in the HEC RAS unsteady flow model, as discussed in Chapter 7.

5.2 Application of the Terrain Model to the MIKE 11 GIS Interface

The MIKE 11 GIS extension uses a Grid-based terrain model instead of a TIN-based terrain model. The MIKE 11 GIS interface in Arcview GIS has the capability to edit the terrain model, but the modifications accomplished previously for this study remove the need for editing. The Grid-based terrain model was developed from Arcview GIS by converting the TIN theme to a Grid-based theme. The Grid mesh was defined as 5-meter by 5-meter cells. The Grid-based terrain model was called

Pdcdem.

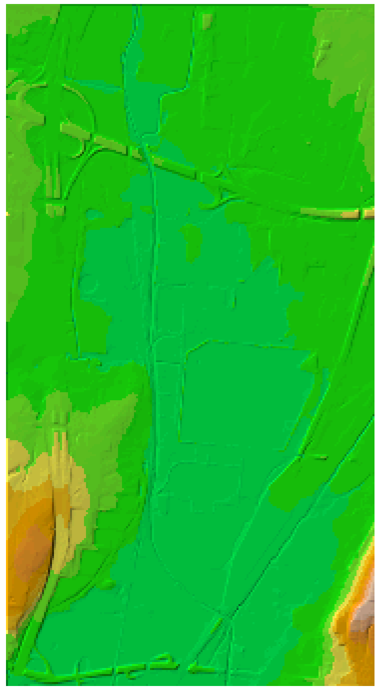


Figure 5-14. The PDC Grid-based terrain model shown with hill shading effect.

A disadvantage of the Grid-based terrain model is poor resolution as compared to the TIN-based terrain model. As shown in Figure 5-15, the water surface delineation with the terrain creates a rough edge since a grid mesh accomplished the delineation. The Grid-based terrain model requires less computer memory as compared to a TIN-based terrain model. The *Pdcdem* was 450 kilobytes in computer memory size, whereas the TIN-based *Nwtin1* was 4.4 megabytes.

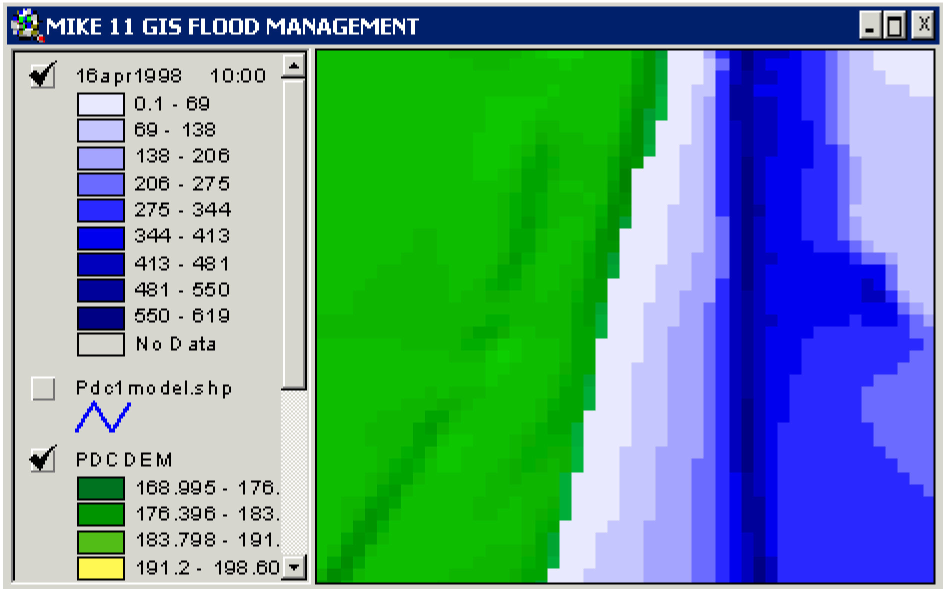


Figure 5-15. Rough edge created when delineating the water surface from the terrain using the MIKE 11 GIS grid-based delineation method.

Chapter 6: Application of the MIKE 11 Model

This chapter discusses the development of the MIKE 11 model as applied to the Mill Creek study area. The three steps to developing the model were processing of the geometric data, inclusion of bed resistance factors, and the integration of flow data from the hydrologic model. Upon completion of model development, simulation results were post-processed in MIKE 11 GIS. The results provided 2-D and 3-D flood animations for the Mill Creek Watershed's 25-year flood event.

6.1 Geometric Processing

As discussed in Chapter 3, the MIKE 11 model consists of two geometric files – the network file and the cross-section file. This section explains how the processed data was incorporated into the MIKE 11 flow model.

6.1.1 Stream Network Development

The stream network used for the MIKE 11 model was the network digitized and saved as *stream1.shp* in Arcview GIS. The X- and Y-coordinates were added to the databases of the *Millpdcreachpts.shp* and *Eastpdcreachpts.shp* point themes (stream points defining *stream1.shp*). The XY-coordinates in the databases were copied into the tabular view of the MIKE 11 network file editor. Using the *Define Branch* tool in MIKE 11, the data points were connected to create the network file. The network file was saved as *pdc1model.nwk11*.

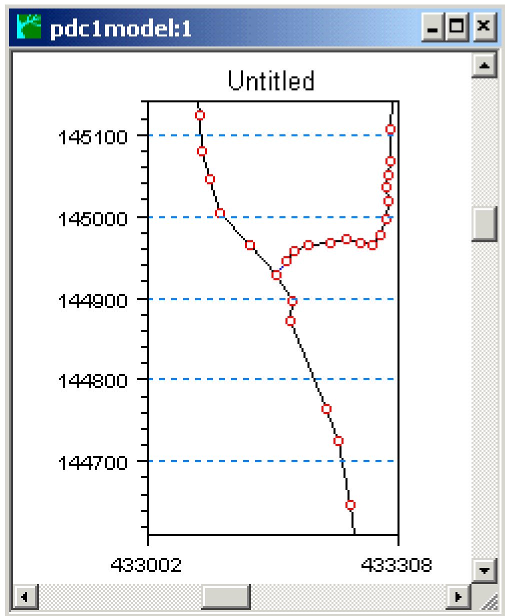
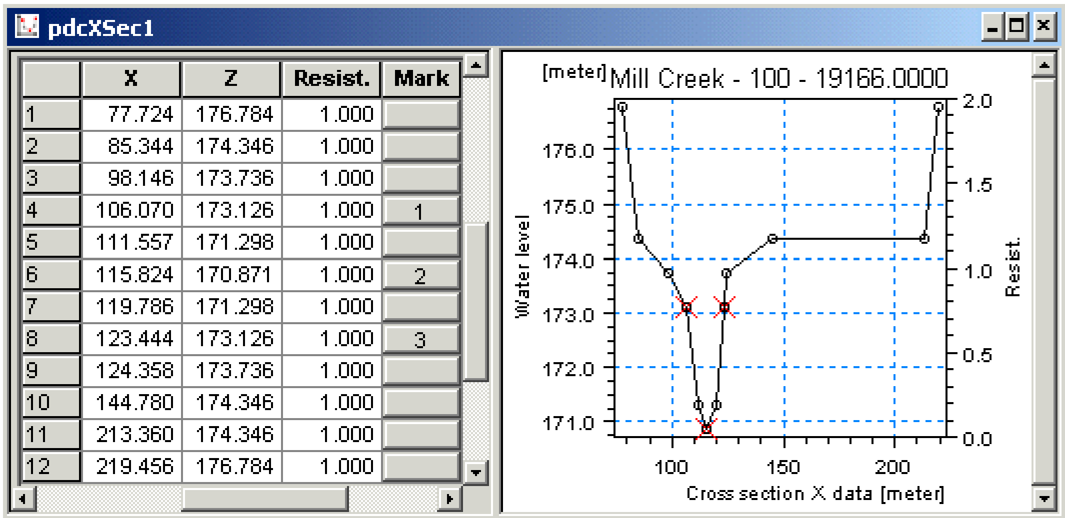


Figure 6-1. MIKE 11 Stream network created with the *Define Branch* tool, from point to point. The figure shows the location where East Fork flows into Mill Creek.

6.1.2 Cross-section Data Development

Upon conversion of the HEC-2 geometry files into readable text files for the MIKE 11 interface, the surveyed cross-section data was imported into the MIKE 11 cross-section file editor. The cross-section file required manual editing of the Chainage values for each cross-section (which was defined as River Stations in HEC-2), and streambed and stream bank locations for each cross-section. The Chainage values were inputted for each cross-section using the conversion table in Appendix A. The stream bank and the streambed locations, as identified in the HEC-2 files, were defined in the cross-section editor using the MIKE 11 *Mark* tool. The *Mark* tool defined a number 1, 2, or 3 along the cross-section in the MIKE 11 cross-section editor. Mark 1 defined the left stream bank, Mark 2 defined the streambed (or centerline), and Mark 3 defined the right bank. Figure 6-2 shows an example of the MIKE 11 cross-section file's streambed and stream bank locations.



	X	Z	Resist.	Mark
1	77.724	176.784	1.000	
2	85.344	174.346	1.000	
3	98.146	173.736	1.000	
4	106.070	173.126	1.000	1
5	111.557	171.298	1.000	
6	115.824	170.871	1.000	2
7	119.786	171.298	1.000	
8	123.444	173.126	1.000	3
9	124.358	173.736	1.000	
10	144.780	174.346	1.000	
11	213.360	174.346	1.000	
12	219.456	176.784	1.000	

Figure 6-2. Cross-section #19166 in MIKE 11. The Marks 1, 2, and 3 are identified on the cross-section's graphical view as red "*X*"s.

Interpolation of cross-sections at the Primary Damage Center model's upstream and downstream boundaries was required. The new bounding cross-sections were interpolated from corresponding upstream and downstream surveyed cross-sections from the HEC-2 files. The interpolated cross-sections were located at Chainage #15407.15 (Mill Creek's upstream boundary), #11427.12 (East Fork's upstream boundary), and #20732.45 (Mill Creek's downstream boundary). Once all editing was completed, the MIKE cross-section file was saved as *pdcXSec1.xns11*.

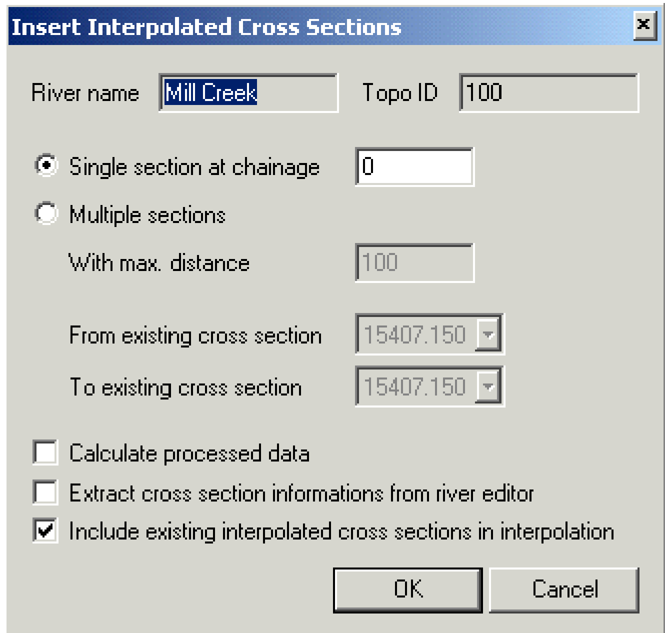
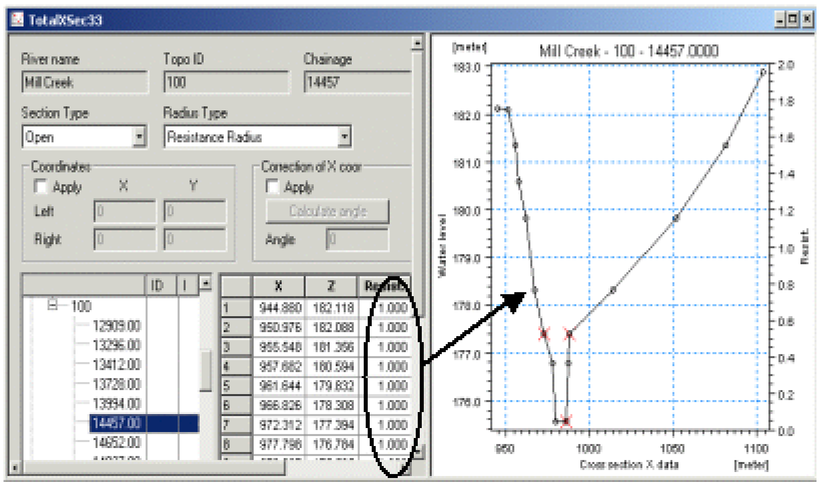


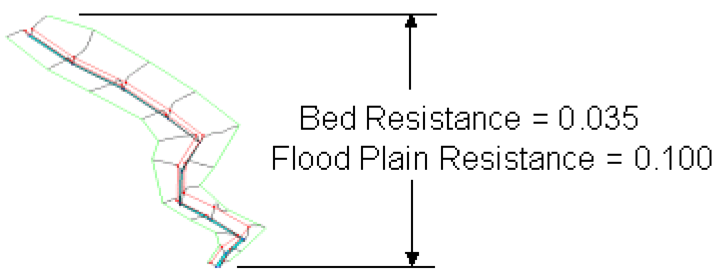
Figure 6-3. The MIKE 11 Cross-section interpolation tool. The cross-section interpolation at the model's boundaries was accomplished using cross-sections outside the PDC terrain model's boundaries from previous MIKE 11 models.

6.2 Bed Resistance Factors

Bed resistance is defined in two different files in the MIKE 11 model. Bed resistance values are defined for a segment of the stream network, from an upstream cross-section location to a downstream cross-section location, using the MIKE 11 hydrodynamic file editor. Bed resistance factors are also defined in the MIKE 11 cross-section file editor. The overall resistance for the model is the product of the resistance factors in the cross-section file and the hydrodynamic file. An example of the resistance factors defined in the two MIKE 11 files are shown in Figure 6-4. The resistance factor in the MIKE 11 cross-section file for each cross-section was set to a default of 1. The Manning's *n* values were extracted from the HEC-2 geometry data and manually inputted as bed resistance and flood plain resistance values in the hydrodynamic file. The *Marks* tool in the MIKE 11 cross-section file editor delineates the stream channel from the flood plains, defining where the bed resistance values change along the cross-section. Once the bed resistance factors were manually inputted into the MIKE 11 hydrodynamic file, the file was saved as *HDPar1.hd11*.



a) Cross Section File (Resistance Factor set to default of 1)



b) Hydrodynamic File (Resistance Factor defined along stream network)

Overall Resistance Factor = Product of Cross Section and Hydrodynamic Resistance Factors

Figure 6-4. The overall resistance factors in the MIKE 11 model are the product of a) the Cross-section File resistance factors, and b) the Hydrodynamic File resistance factors.

6.3 Boundary Conditions

The PDC MIKE 11 model contained two separate boundary condition sets. The first boundary condition set established base flow conditions for the model. The second boundary condition set modeled the 25-yr storm event for the Mill Creek Watershed. In essence, the first set was a steady-state solution of the unsteady algorithm, establishing mathematically stable initial conditions for the second boundary condition set.

6.3.1 Simulating Base Flow Conditions

The first boundary file created a *hotstart* file (as explained in Chapter 4) for the flow model, establishing base flow conditions. The first MIKE 11 boundary file was *Bnd1.bnd11*. The time-series boundary conditions for *Bnd1.bnd11* consisted of the upstream base flow conditions for Mill Creek and East Fork, and the downstream stage height conditions for Mill Creek. The Mill Creek stage height was set to 169.3 meters.

The base flow conditions were run for a 10-day period using a 10-minute time step. The simulation was saved as *pdc1hotstart.sim11*, and was used as the initial conditions for the second set of boundary conditions.

6.3.2 Incorporating Hydrologic Data as Boundary Conditions

The second set of boundary conditions simulated the runoff effects on the PDC study area for the 25-year storm event. The upstream, downstream, and lateral boundary conditions were obtained from the HEC HMS hydrologic model of the Mill Creek Watershed. The hydrologic data used is shown in Appendix E. The time-series data could not be exported directly from the HEC HMS model for use in the MIKE 11 model. The upstream and lateral boundaries defined as runoff and flow hydrographs from the hydrologic model were converted to an *Adobe Acrobat* file as explained in Chapter 3. From the *Acrobat* file, the data was copied into the MIKE 11 time-series file editor. The time step used in the HEC HMS model was 15-minutes, and the same time step was used for the runoff hydrograph inflows in the MIKE 11 model.

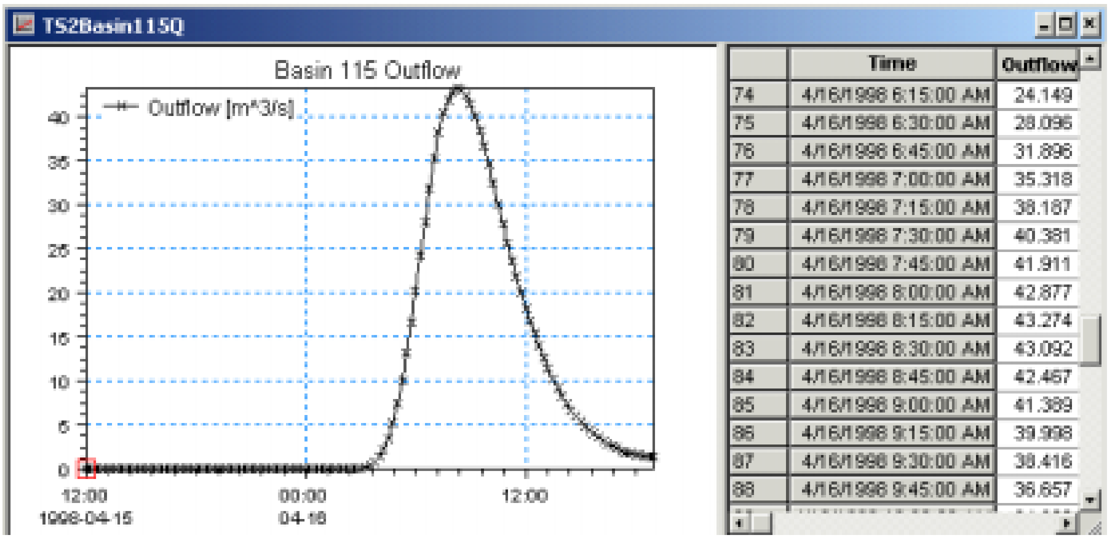


Figure 6-5. A MIKE 11 time-series file extracted from the HEC HMS hydrologic model. The time step used is 15-minutes.

The Chainage location for each lateral inflow hydrograph was determined by importing the HEC HMS model schematic into the MIKE 11 river network file. By overlapping the network file on top of the watershed schematic, the Chainage location of each watershed outlet was determined and established as a lateral boundary condition in the MIKE 11 boundary file.

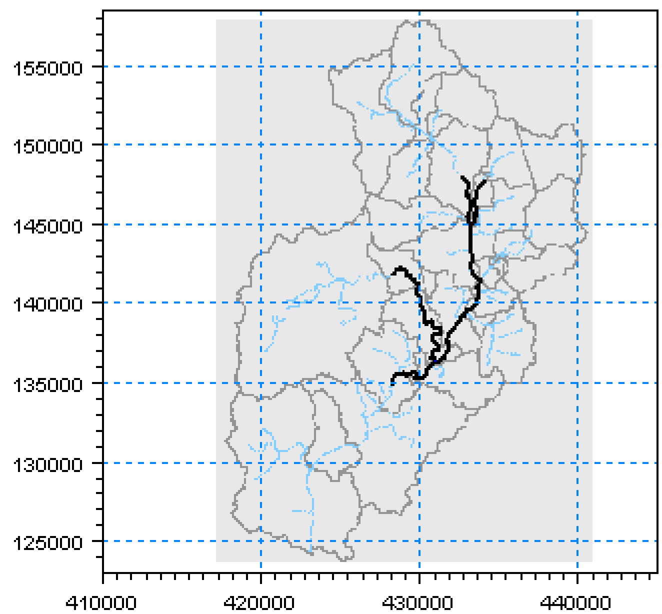


Figure 6-6. The Mill Creek HEC HMS schematic imported as a background image into the MIKE 11 river network file. The schematic was used to identify Chainage values at watershed outlets.

The downstream boundary condition, a time-series stage hydrograph, was not available. Successive runs of the model at different steady-state flows were used to determine the downstream hydrograph. The stage height values were interpolated for intermediate time steps. Further modifications of the stage hydrograph were required to fit the stage height corresponding to the inflow, by viewing the longitudinal profile results in *MIKE View*.

Since the PDC study area was a smaller section of the initial study area, upstream and downstream boundary conditions were extracted from the results of previous models. Previous model simulation results used a 4-minute time step, thus the time-series data was set to a 4-minute time step as well. The difference in time steps for the upstream and downstream boundaries as compared to the lateral boundaries did not affect the MIKE 11 model results.

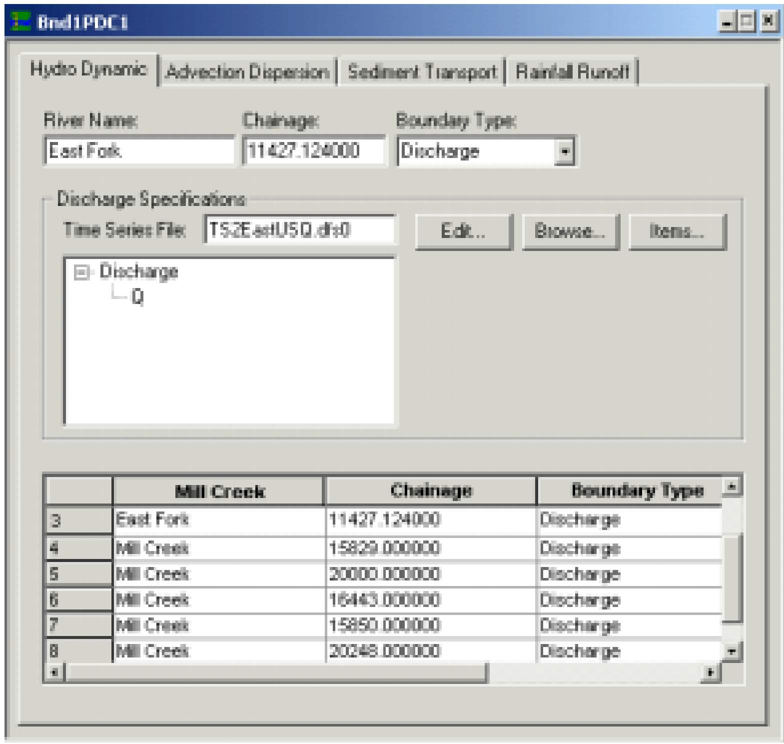


Figure 6-7. A MIKE 11 boundary file. The boundary file connects the upstream, downstream, and lateral inflow hydrographs to Chainage values along the network.

Setting the *hotstart* file as the initial condition and the time-series runoff and flow hydrographs from the HEC HMS model as boundary conditions, the MIKE 11 model was run using a 4-minute time step over a 31-hour time range. Results of the model were observed in *MIKE View* for any necessary editing. Using the longitudinal profile in MIKE View for stage height and discharge, time-series changes transitioned smoothly between time steps. Some random fluctuation in stream flow was observed at the East Fork tributary. Additional cross-sections were interpolated there to provide less severe jumps in streambed elevations. This alleviated some of the stage height fluctuation at that location.

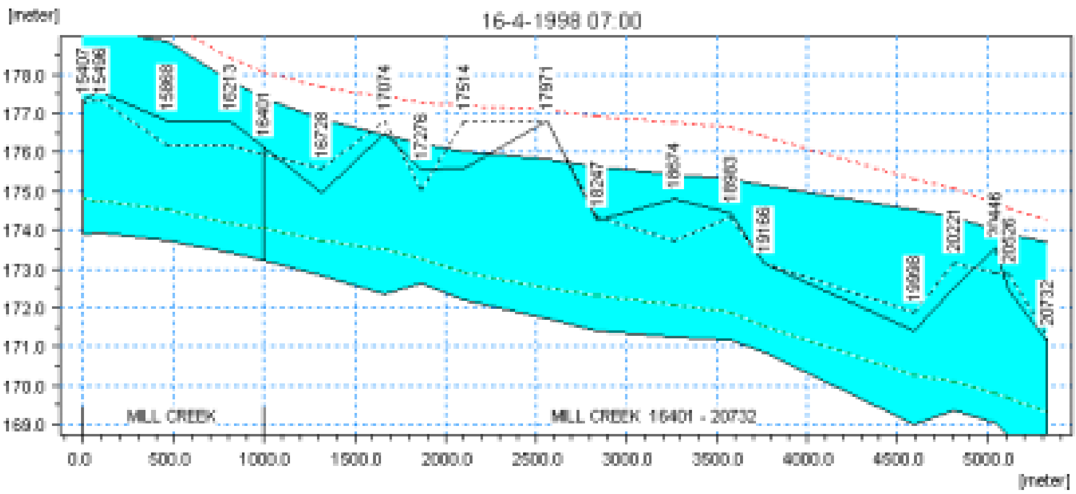


Figure 6-8. A profile of Mill Creek in the PDC study area. The red dotted line denotes maximum stage height; the green dotted line denotes base flow. Initially, stage fluctuation occurred at the East Fork tributary (Chainage #16401).

6.4 Post Processing in MIKE 11 GIS

Once the MIKE 11 model of the Mill Creek PDC was run simulating the 25-yr storm event (April 1998 storm), the data was imported into Arcview GIS for flood visualization purposes. The MIKE 11 model accomplished this by linking the unsteady flow results with the terrain model through the *Branch Route System*, which is the MIKE 11 river network file. The MIKE 11 river network file linked the MIKE 11 simulation data (saved as *pdc1.msd*) to corresponding XY-coordinate locations on the terrain model.

6.4.1 Geo-referencing the Stream Network to the Terrain Model

Since the MIKE 11 river network file was initially created from the terrain model, the network was already geo-referenced, making the link between the unsteady flow simulation and Arcview GIS effortless. When opening the MIKE 11 GIS *Flood Management* Tool, the interface automatically asked the user for the MIKE 11 river network file and the MIKE 11 simulation data results.

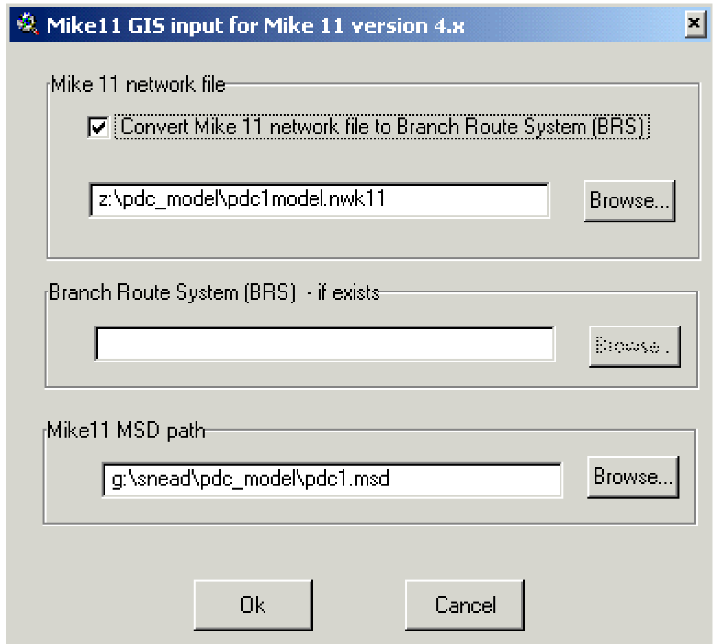


Figure 6-9. The MIKE 11 flow model inputs for MIKE 11 GIS: the river network file and the simulation data.

6.4.2 Importing Q and h Data into MIKE 11 GIS

The Q- and h-points were imported into the Arcview GIS interface from the MIKE 11 network file data. The Q-points are average flows at the midpoint of each finite segment within the model (half the distance between successive cross-sections). The h-points are stage heights at upstream and downstream finite segment boundaries (cross-section locations). The simulation data (*pdc1.msd*) was spatially imported to each corresponding Q- or h-point along the stream network, using the Chainage values for geo-referencing. The result was the creation of two point themes in Arcview GIS, *Qpoints.txt* and *Hpoints.txt*.

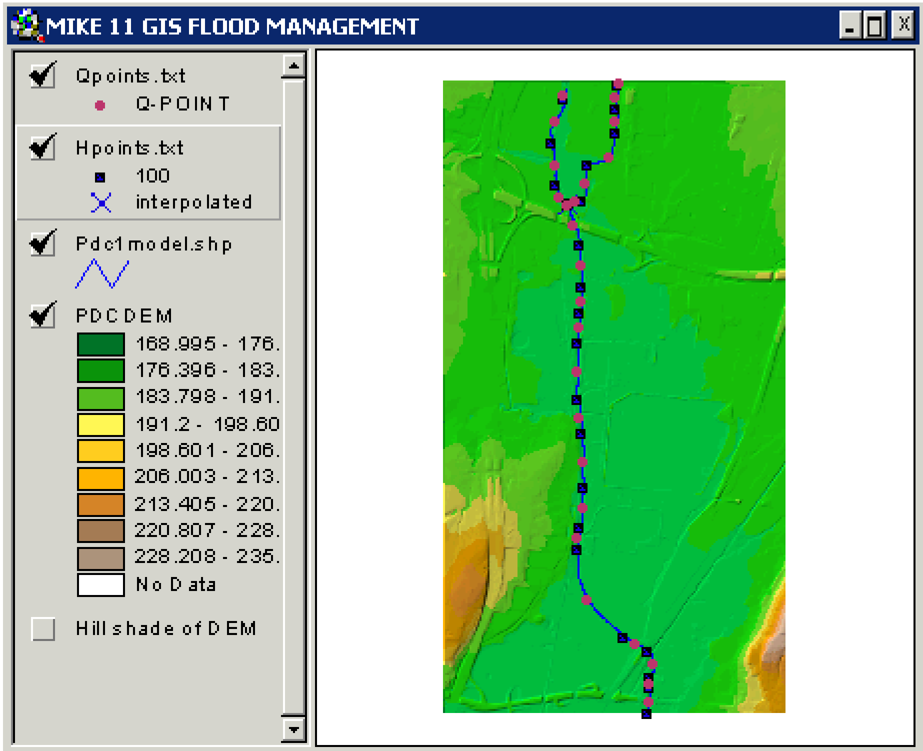


Figure 6-10. Q-points and h-points imported into MIKE 11 GIS. Q-points are located between two corresponding cross-sections; h-points are located at each cross-section.

The *Hpoints.txt* theme is the required MIKE 11 flow model data for flood delineation. MIKE 11 GIS linked the *pdc1.msd* data to the corresponding record in the *Hpoints.txt* theme's attribute table. As shown in Figure 6-11, water surface elevations for cross-section at each time step from the MIKE 11 flow model were imported into the *Hpoints.txt* attribute table.

Attributes of Hpoints.txt

Chainage	Topo_id	Type	15apr1998 12:0	15apr1998 12:0	15apr1998 12:04	15apr1998 12:0
17514.000000	100	0	172.884	172.884	172.884	172.884
17971.000000	100	0	172.521	172.521	172.521	172.521
18247.000000	100	0	172.315	172.315	172.315	172.315
18674.000000	100	0	172.078	172.078	172.078	172.078
18983.000000	100	0	171.868	171.868	171.868	171.868
19166.000000	100	0	171.543	171.543	171.543	171.543
19998.000000	100	0	170.271	170.271	170.271	170.271
20221.000000	100	0	170.125	170.125	170.125	170.125
20446.000000	100	0	169.799	169.799	169.799	169.799
20526.000000	100	0	169.676	169.676	169.676	169.676
20732.000000	100	2	169.324	169.324	169.324	169.324
11465.000000	100	0	175.545	175.545	175.545	175.545

Figure 6-11. MIKE 11 flow model results were imported into the *Hpoints.txt* attribute table. Water surface elevations at each cross-section are represented for each time step.

6.4.3 Generating Flood Maps and Animations from the Unsteady Flow Model

Using the *Hpoints.txt* data, flood maps were developed in MIKE 11 GIS for user-specified time steps. A water level surface grid was interpolated using inverse distance-weighted interpolation of the nearest h-points. The difference between the water level surface grid and the terrain model grid created flood maps. Figure 6-12 shows the water surface elevation at 10:00 am on April 16, 1998.

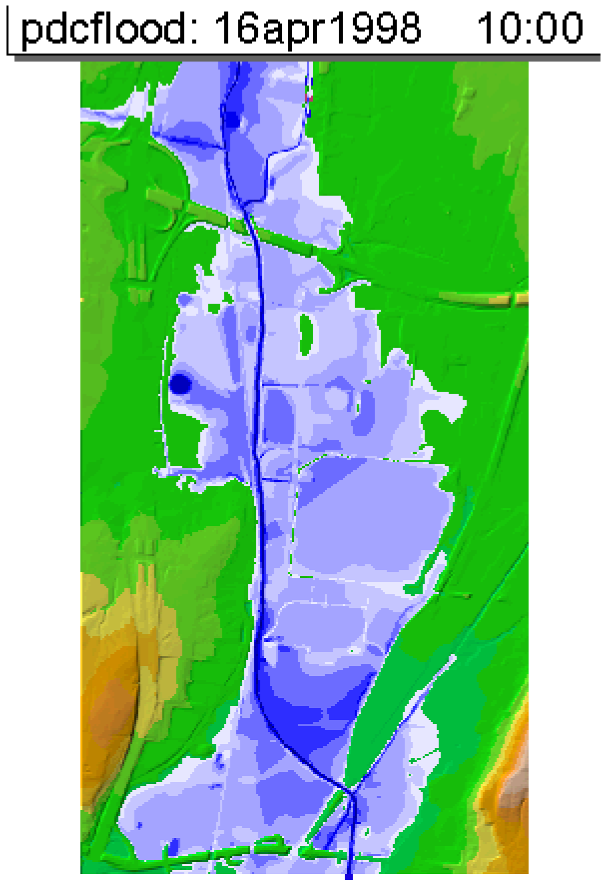


Figure 6-12. Flood map of the Mill Creek PDC developed from MIKE 11 model data.

3-D animations and “fly-bys” were also developed in MIKE 11 GIS. Buildings were added to the animations for reference purposes. An advantage to using MIKE 11 GIS for flood visualization is the simplicity of low memory, grid-based models for processing. The major disadvantage is that the 2-D and 3-D grid-based images depict a rough edge where the water surface is delineated from the terrain model.

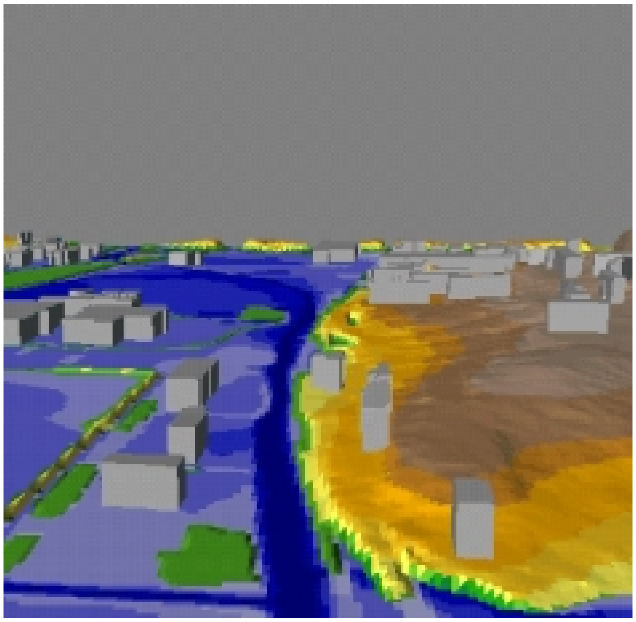


Figure 6-13. Snapshot from a MIKE 11 “Flyby” animation. Notice the rough edge where the water surface is delineated from the terrain.

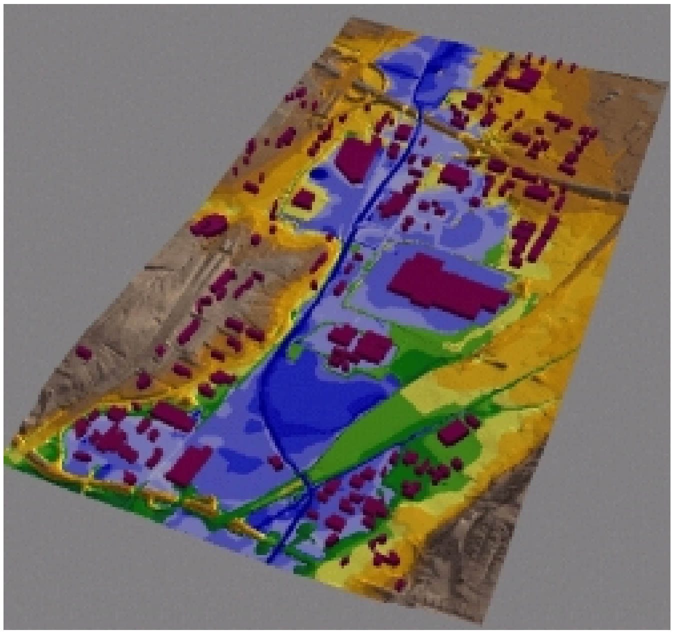


Figure 6-14. 3-D animation of the Mill Creek PDC with buildings. The image shows the peak stage height for the 25-yr storm event.

Chapter 7: Application of the HEC RAS Model

The four steps to flood visualization using the HEC RAS flow model and the HEC GeoRAS extension were 1) extraction of the stream geometry data from the modified terrain model for use in the HEC RAS unsteady flow model, 2) processing the geometry data in HEC RAS, 3) integration of hydrologic data as initial conditions and boundary conditions in the HEC RAS unsteady flow data file, and 4) post-processing (i.e. flood visualization) of HEC RAS model results in Arcview GIS. Unlike the MIKE 11 model, the stream geometry was extracted from the terrain model and incorporated into the unsteady flow model, maintaining spatial referencing between the model and the Arcview GIS environment. Flood delineation with the terrain model was limited by the bounding polygon created by HEC GeoRAS pre-processing, which required several iterations of the stream geometry extraction to attain an optimum solution.

7.1 Extracting Stream Geometry from the Terrain Model

Geometry data extracted from the modified terrain model is similar to having a "virtual" surveying team on the surface of the terrain model. The modeler identifies what stream data is needed, and the HEC GeoRAS extension extracts the data from user-defined locations on the terrain model. The data locations required are the stream's centerline, stream banks, stream cross-sections, stream channel flow path, and flood plain flow paths.

To assist in the process, digital orthographic photo images or USGS quadrangle sheets can assist the modeler when defining the stream geometry with respect to the terrain model. For this study, the TIN-based terrain model was used to differentiate stream banks from the rest of the terrain. The stream centerline was already defined, using the *stream1.shp* theme. An iterative process was used to define flood plain flow paths and the extent of cross-sections. Importing the geometry data into HEC RAS, running a simulation, and then viewing the results in Arcview GIS using the *postRAS* menu accomplished this process. If the cross-sections limited the extent of the flooding, then the cross-sections were extended and the process was repeated. After six iterations, the optimum results were developed.

7.1.1 Developing the Stream Centerline and Main Channel Banks

The stream centerline theme was copied from the previously developed *stream1.shp* theme. The stream centerline theme was saved as *Pdcstream.shp*. Using the *River ID* tool, each section of the stream centerline was defined with a *Stream_ID* and *Reach_ID*. Based on the terrain data, lengths of each section in the stream centerline were calculated. Results from using the *River_ID* tool are shown in Table 7-1. The Nodes shown in the table are defined accordingly: Node #1 – upstream boundary of East Fork, Node #2 – East Fork tributary connection with Mill Creek, Node #3 – upstream boundary of Mill Creek, and Node #4 – downstream boundary of Mill Creek.

Table 7-1. River ID data for each reach in the PDC stream network.

Stream_ID	**Reach_ID**	**From Node**	**To Node**	**Length (ft)**	**From RS#**	**To RS#**
Eastfk	Eastfk	1	2	1217.381	1217.381	0.0
Millcrk	MillcrkUS	3	2	1029.274	5190.737	4161.464
Millcrk	MillcrkDS	2	4	4161.464	4161.464	0.0

The main channel banks were digitized based on the terrain model. Differences in slope found in the TIN mesh were identified and used to distinguish the extent of the stream banks. Once the digitizing was complete for both the Mill Creek and East

Fork stream banks, the theme was saved as *Pdcbanks.shp*. Any significant irregularities with defining the main channel banks were adjusted in HEC RAS by redefining the boundary between the flood plains and the stream channel.

Figure 7-1. Stream centerline and main channel banks defined for East Fork on the TIN-based terrain model. Changes in the TIN mesh's slope assisted with digitizing the main channel banks.

7.1.2 Developing Cross-section Cut Lines and Flow Paths

The cross-section cut line locations in HEC GeoRAS were initially established as the cross-section locations defined in the HEC-2 files. Through an iterative process, it was determined that the HEC- 2 cross-section locations limited the extent of the flood plain and required to be extended well beyond the initial surveyed cross-section extents. To also minimize overlapping of cross-sections, the cross-section cut lines were shifted to different locations along the stream network. The cross-section cut lines theme was called *Xscutlines.shp*.

Figure 7-2. The HEC-2 cross-sections (blue) and the GeoRAS cross-section cut lines (green, with arrows) shown along the stream network in the terrain model. The cross-section cut lines were extended beyond the extent of the flood plain and shifted to prevent cross-section overlap.

Flow paths were defined for the stream centerline, and the left and right flood plains. Flow paths were used in HEC RAS to determine downstream reach lengths. Using the *Label flowpaths* tool, the flow path for the stream centerline was identified as *Channel*, the left flood plain as *Left*, and the right flood plain as *Right*. The flow path theme was called *Pdcflowpath.shp*.

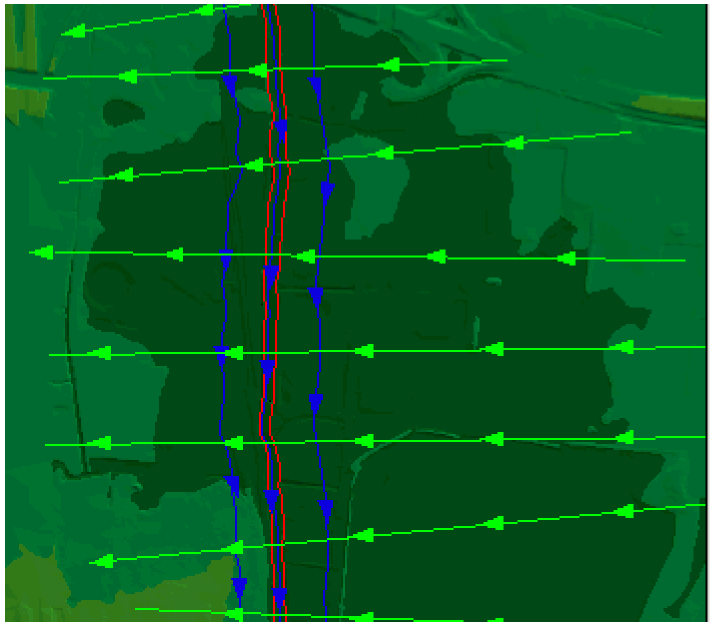


Figure 7-3. Flow paths (shown in blue), channel banks, and cross-section cut lines defined with respect to the PDC terrain model.

7.1.3 Generating the RAS GIS Import File from Terrain Data

HEC GeoRAS extracts 3-D features from the terrain model corresponding to the stream centerline, main channel banks, cross-section cut lines, and flow path themes. The digitized themes were selected for input into the HEC GeoRAS pre-processing. Each digitized theme was identified in the *Theme setup* menu. As shown in Figure 7-4, there was no *Land use* theme identified for this study. The land use theme is an optional step in the GeoRAS pre-processing which allows the modeler to extract Manning's *n* values based on a spatial land use corresponding to the terrain model. For this study, the Manning's resistance factors were inputted into the HEC RAS geometry file manually.

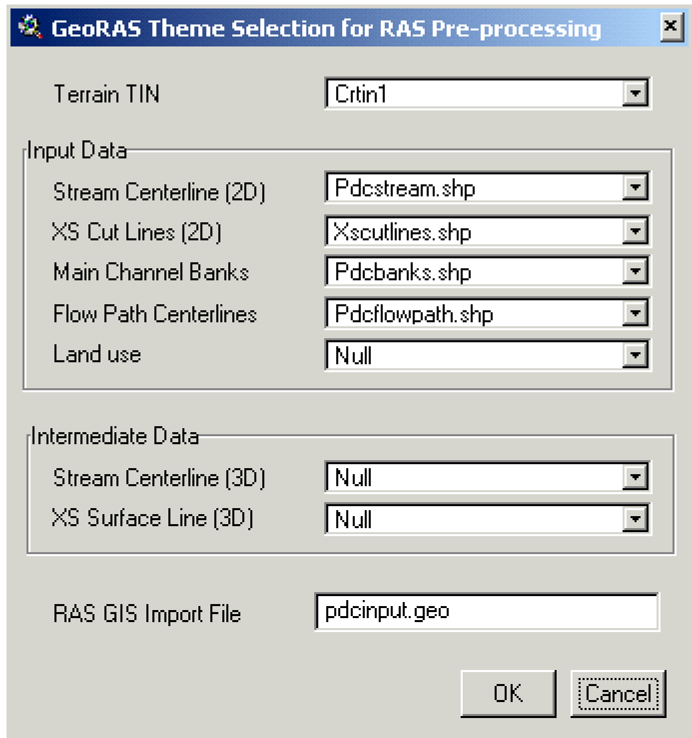


Figure 7-4. Theme setup menu for GeoRAS pre-processing.

The intermediate data shown in Figure 7-4, the *Stream Centerline (3D)* and the *XS Surface Line (3D)*, was created during the HEC GeoRAS pre-processing. The 3-D themes created from the pre-processing were called *Pdcstream3D1.shp* and *Xscutlines3D1.shp*, respectively. Once the pre-processing was completed, the *RAS GIS Import* file (defined as *pdcinput.geo*) was processed and imported into HEC RAS. The import file developed was a text file containing the pertinent geometry data for use in the HEC RAS unsteady flow model.

7.2 Geometric Processing

Once the geometry data from HEC GeoRAS was imported into the HEC RAS geometry data editor, two additional edits were required to further refine the geometry data. Each cross-section's bank station locations required verification and bed resistance factors required input into the model.

Bank stations may have not been placed correctly in each cross-section from the digitized main channel banks using HEC GeoRAS. In such cases, the bank stations were adjusted to best define the stream channel for each cross-section. As shown in Figure 7-5, the right bank station was shifted up and to the right to the best location defining the natural stream channel in the cross-section.

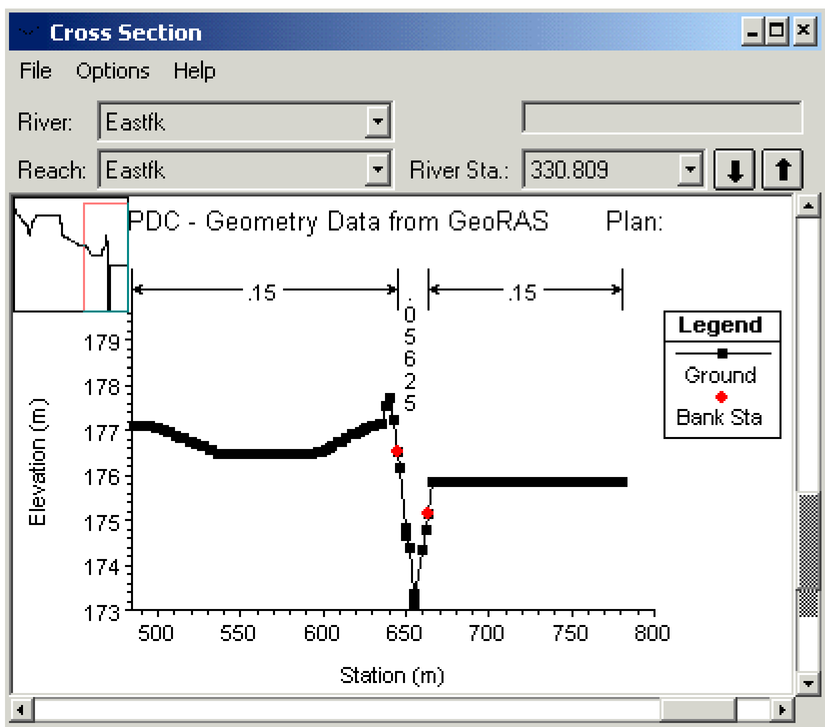


Figure 7-5. The right bank location shown was shifted up and to the right to depicting the most natural transition from flood plain to streambed.

7.2.1 Import GIS Stream Geometry Data

The data extracted from the HEC GeoRAS pre-processing was imported into the HEC RAS geometry data editor. Under the *Import Geometry data* command in the HEC RAS geometry data editor, the *GIS Format* option was chosen and the *pdcinput1.geo* file was highlighted. The schematic of the imported geometry data is shown in Figure 7-6. Since the geometry data was extracted in unit of meters, the River Stationing was also in meters. HEC GeoRAS automatically determined the River Stationing, thus there was no correlation with the previous HEC-2 River Stations.

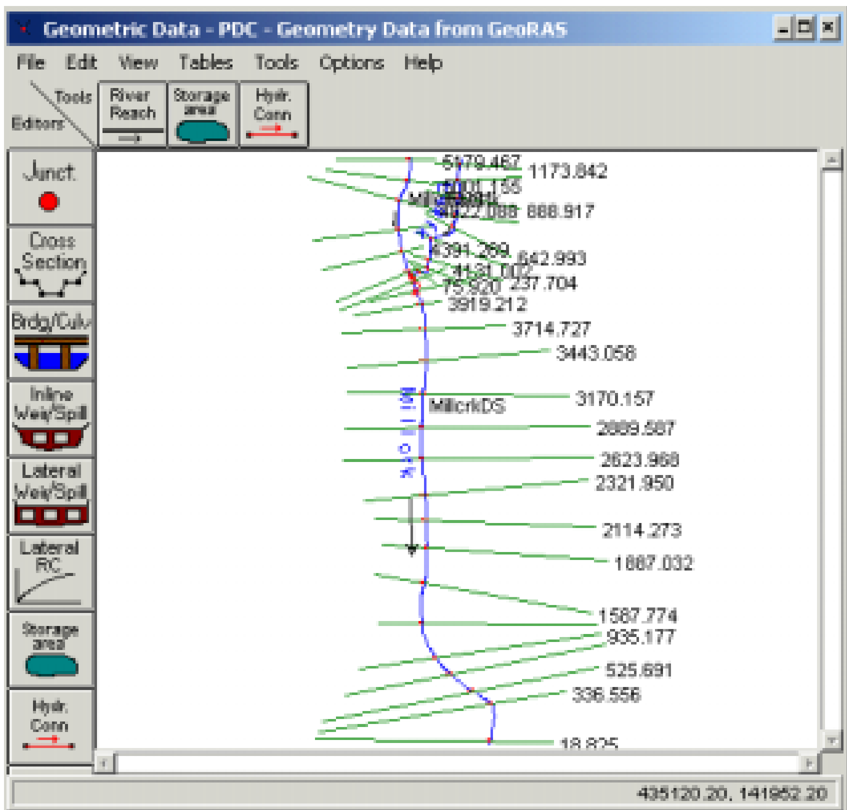


Figure 7-6. The HEC RAS geometry data schematic of the GIS imported data. The numbers are the River Stations for each cross-section.

7.2.2 Bed Resistance Factors

Bed resistance factors in HEC RAS are inputted for each cross-section in the geometry data editor. Since the Manning resistance factors were not imported from the RAS GIS import file, the Manning's *n* values were manually inputted for each cross-section, using the data included in the HEC-2 files. The Manning's *n* values stayed constant for the streambed and flood plains for each reach in the stream network, thus no interpolation of resistance factors at any cross-section was required.

7.3 Development of Unsteady Flow Initial Conditions and Boundary Conditions

Initial conditions and boundary conditions for the HEC RAS model were extracted from flow, stage, and/or hydrologic time-series data corresponding to the specific model area. For the unsteady flow model, the time-series data is inputted into the *Unsteady Flow Data* editor. The data inputted into the editor are *Initial Conditions* and *Boundary Conditions*.

7.3.1 Establishing Initial Conditions as Base Flow

The initial flow conditions were inputted into the Unsteady Flow Data editor using the base flow conditions for Mill Creek and East Fork. For continuity purposes, the initial flow for the Mill Creek reach downstream of the East Fork tributary was 2.43 m^3/s, the sum of the two upstream base flows (as shown in Figure 7-7).

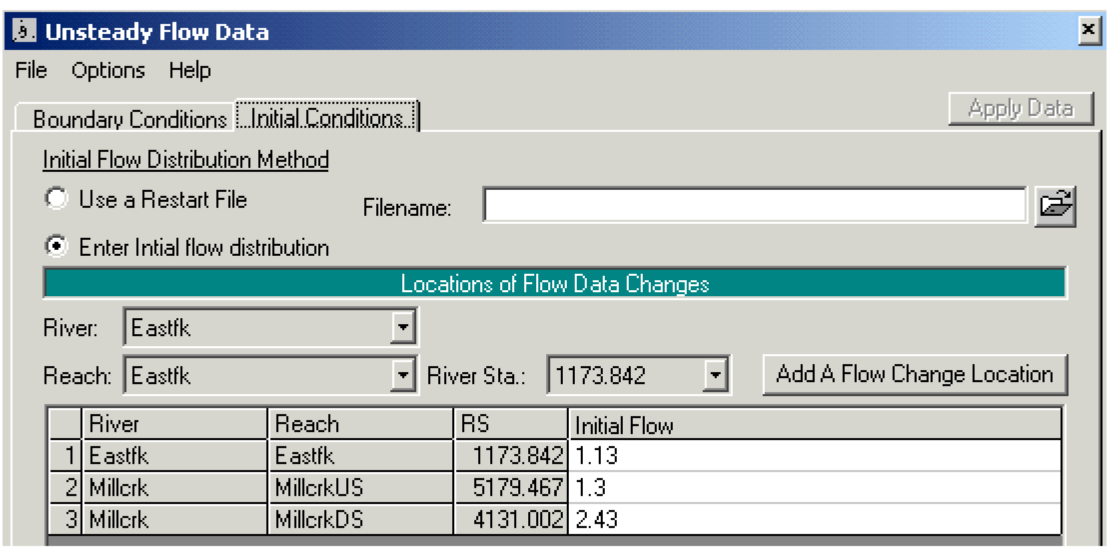


Figure 7-7. Initial flow conditions used for the HEC RAS model, in m^3/s.

7.3.2 Boundary Conditions Derived from the Hydrologic Data

The boundary conditions were obtained from the HEC HMS model of the Mill Creek Watershed. The HEC RAS model linked with the HEC HMS model results saved in a DSS file. The HEC RAS model interface extracted pertinent time-series data from the specified DSS file.

The HEC HMS model interface automatically saved the results as a DSS file called *MllCreek_CSO.dss*. Unlike the MIKE 11 model, where lateral inflows (at watershed outlets) can be entered at *any* location along the stream network, lateral inflows in the HEC RAS model can only be entered at a cross-section location. Thus, the runoff hydrographs at the watershed outlets were connected to the nearest downstream cross-section along the stream network.

7.3.2.1 Corresponding Stream Flow and Runoff Hydrographs

Since the MIKE 11 model size was decreased from previously developed flow models, the upstream and downstream flow and stage hydrographs were copied from the previous models into the current HEC RAS model. All watershed hydrographs were extracted from the HEC HMS model via the DSS utility. One watershed outlet along the HEC RAS model included the inflow from five watersheds, so the hydrologic data was imported from the DSS file as an *Outflow* hydrograph at Junction #23 in the HEC HMS model. Table 7-2 shows the source of the hydrograph data used for the HEC RAS model, along with the watershed outlet referencing that corresponded with the MIKE 11 model.

Table 7-2. Hydrograph sources for the HEC RAS model

Description	**River Station (m)**	**Corresponding MIKE 11 Chainage (m)**	**Data Source**
Mill Creek			
Upstream Boundary	5179.47	15407.15	MIKE 11 model
Basin 109 runoff	4822.088	15829.00	DSS file
Basin 115 runoff	525.691	20000.00	DSS file
Basin 110 runoff	4043.303	16443.00	DSS file
Basin 111 runoff	4577.873	15850.00	DSS file
Basins 112 thru 117 runoff (Junction #23 outflow)	336.56	20248.00	DSS file
Downstream Boundary	18.83	20732.45	MIKE 11 model
East Fork			
Upstream Boundary	1173.84	11427.12	MIKE 11 model

7.3.2.2 Extracting Hydrographs using the DSS Utility

When defining a boundary condition hydrograph, the time-series data can either be entered directly into the editor, or read from a DSS file. The DSS file data was imported into the HEC RAS model by defining the boundary condition as *Lateral Inflow* in the *Unsteady Flow Data* editor. Highlighting the *Read from DSS file* option, the HEC HMS *Mllcreek_CSO.dss* file was opened. From the DSS file, the hydrograph pertaining to the watershed outlet in the HEC RAS stream network was highlighted, making the connection between the HEC RAS model and the HEC HMS hydrograph data. An example of the DSS connection is shown in Figure 7-8. The figure depicts the connection with the *Flow* hydrograph for *Basin #109*, with a *15-minute* time step, for *Run #16* of the HEC HMS model. The DSS utility imported the hydrograph into the HEC RAS model for River Station #4722.088. From the DSS Path window, the hydrograph was graphically plotted to ensure the correct data was extracted from the HEC HMS model.

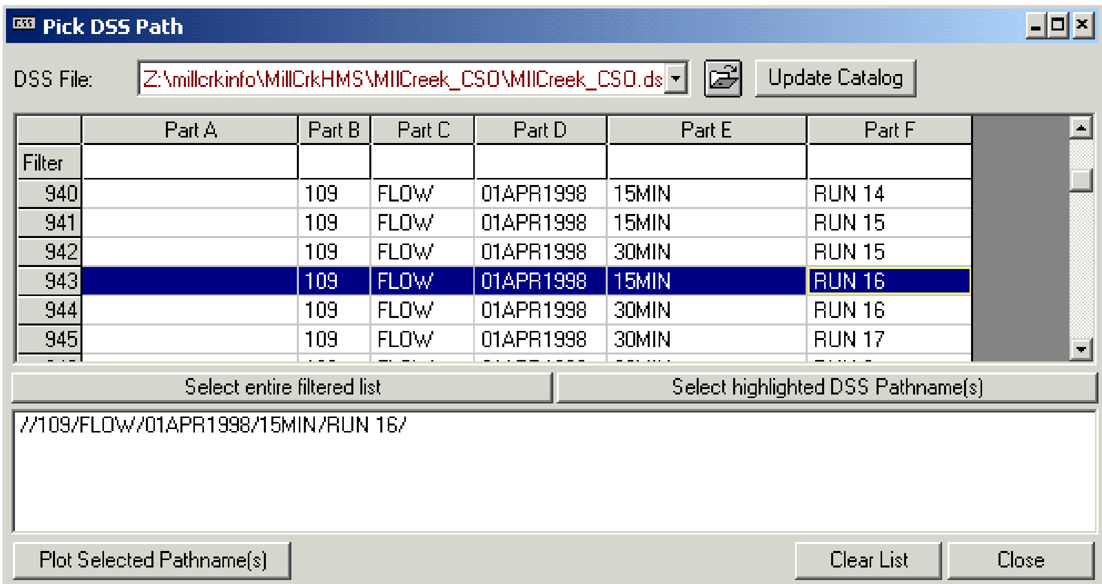


Figure 7-8. The *DSS Path* window in HEC RAS. The window imports hydrograph data from a HEC HMS *DSS file* into the HEC RAS *Unsteady Flow Data* file.

7.4 Unsteady Flow Simulations in HEC RAS

The simulation plan for the HEC RAS model was the same as for the MIKE 11 model. The plan is shown in Figure 7-9. Using a 4-minute time step, the range of the simulation ran from 12:00 pm on April 15, 1998 to 7:00 pm on April 16, 1998 (31 hour time duration). The hydrograph output interval was set to 30-minutes to decrease the overall processing time.

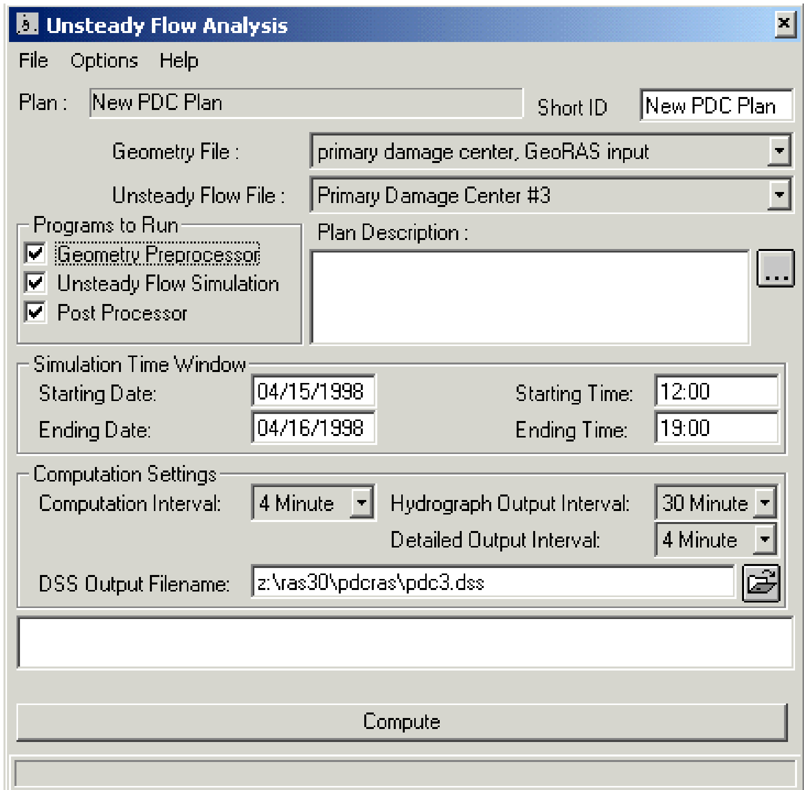


Figure 7-9. The HEC RAS *Unsteady Flow Analysis* plan shown for the Mill Creek PDC model.

The simulation results were graphically displayed a number of ways in the HEC RAS user interface. Simulations were displayed as *longitudinal profiles*, *X-Y-Z perspective plots*, and as *cross-section profiles*. As previously discussed, the geometry extraction process was repeated numerous times until the optimum simulation results were obtained. If the extent of the cross-sections limited the extent of flooding in the HEC RAS model, the process was repeated. Fortunately, additional editing of the flow data was not required.

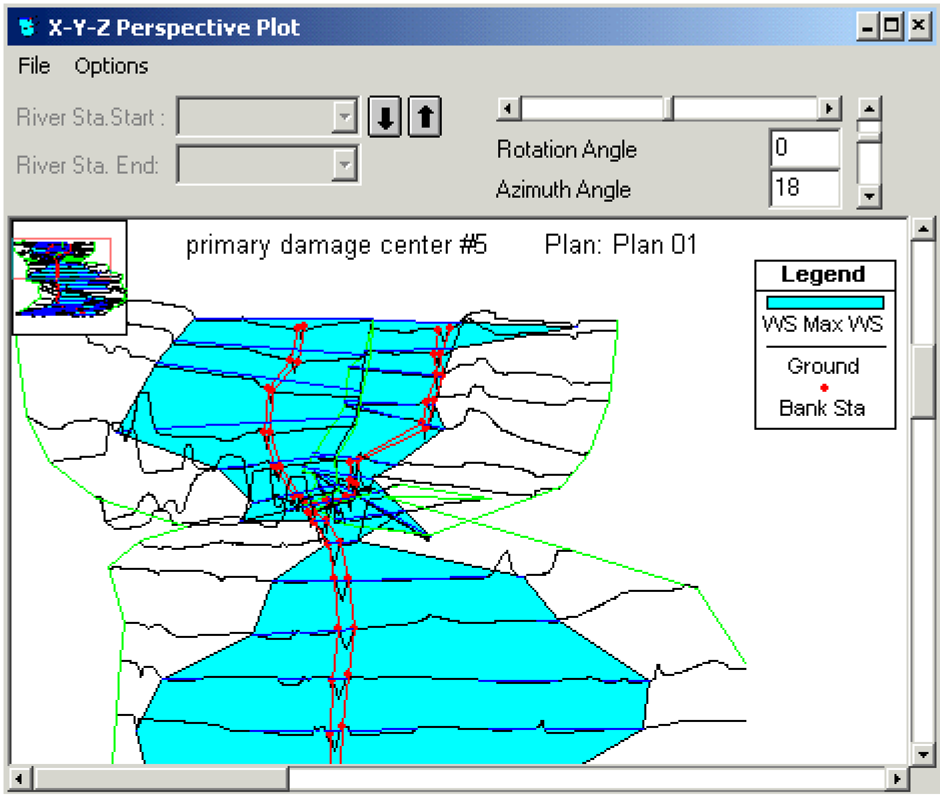


Figure 7-10. The *X-Y-Z Perspective Plot* in HEC RAS. The water level shown is the maximum water surface elevation for the PDC area from the 25-year storm event.

7.5 Post Processing in HEC GeoRAS

Once the optimum simulation was obtained, the data from the simulation was ready for exporting into Arcview GIS for flood visualization. This was accomplished through the HEC GeoRAS *post-RAS* menu. Water surface elevation data created from the HEC RAS model was connected to each corresponding cross-section location for each time step. Since the cross-section and stream channel was created from the HEC GeoRAS pre-processor, the unsteady flow data was already geo-referenced to the modified terrain model.

7.5.1 Read RAS GIS Export File

Once the simulation was complete, the unsteady flow data was exported into Arcview GIS. Time steps from the simulation data were selected for exporting. The HEC GeoRAS *Theme Setup* command in the *postRAS* menu defined the GIS export file created from the HEC RAS model, the modified terrain model, the output directory, and the rasterization cell size used for post-processing. As shown in Figure 7-11, the cell size of 5 was selected, thus the grid-based water surface output had 5-m by 5-m grid cell sizes. Once the *RAS GIS export* file was inputted into GeoRAS, delineation of the water surfaces with the terrain model was the next step.

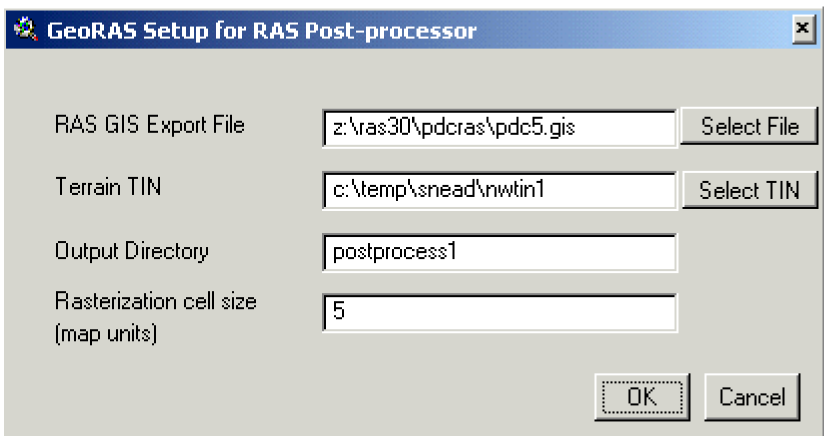


Figure 7-11. For HEC GeoRAS post-processing, the inputs for Arcview GIS were defined.

7.5.2 Water Surface TIN Generation

To accomplish water surface delineation, the shape themes depicting each water surface required conversion to a TIN-based surface. A TIN-based surface was created by interpolating elevations between cross-sections, based on the imported water surface elevations along each cross-section's length. The result was a 3-D, TIN-based surface depicting the water surface at the time step defined in HEC RAS.

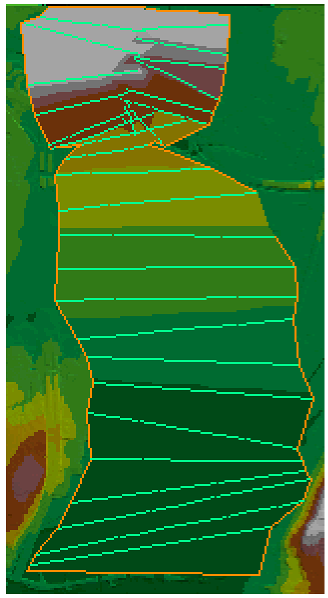


Figure 7-12. The water surface TIN created from HEC RAS input overlapping the terrain model of the PDC study area.

The TIN-based water surface still required three-dimensional delineation with the terrain model surface to create flood visualization. The view shown in Figure 7-12 shows the overlapping of the two TIN-based surfaces. Notice how the cross-sections act as boundaries for the water surface. The subsequent step develops the flood plain.

7.5.3 Delineating Flood Plains from Unsteady Flow Model Results

Once the water surface was created, the flood plain was delineated from the terrain model in the next step. In the two-dimensional plane, the delineation resulted in grid-based themes and shape themes depicting the water surface. The grid-based theme showed the spatial difference in water depth with respect to the terrain model, as shown in Figure 7-13 of the maximum water surface.

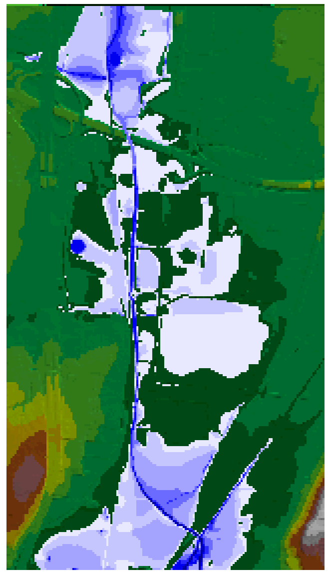


Figure 7-13. Maximum water surface for the April 1998 flood delineated from the terrain model.

Using the delineated shape theme, editing can be accomplished in Arcview GIS to remove water pits or ponds, which can be seen in Figure 7-13. Obviously such editing would not change the overall model, to do so would require either modifications to the cross-sections using the GeoRAS pre-processor, or the establishment of ineffective flow areas for specific cross-sections in the HEC RAS geometry data.

Delineation of the TIN-based water surface from the terrain model was also observed using the *3D Scene* from the Arcview GIS *3D Analyst* extension. The 3D Scene showed the three-dimensional attributes of the Arcview GIS themes in a three dimensional plane. Figure 7-14 displays the delineation of the water surface profile from the terrain model. The entire water surface TIN actually exists in the 3-D view, where the water surface elevations less than the terrain elevation fall underneath the terrain surface and cannot be observed from a perspective above the terrain.

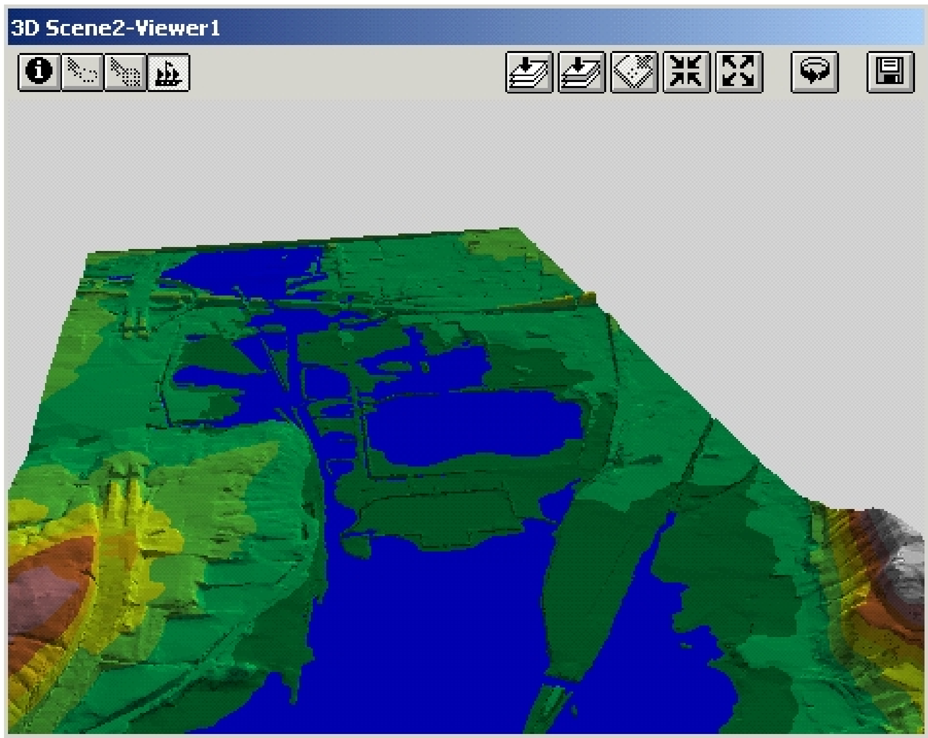


Figure 7-14. Three-dimensional representation of the TIN-based terrain model and water surface using *3D Analyst*.

A significant difference when viewing the results of the HEC GeoRAS interface versus MIKE 11 GIS is along the lines of water surface delineation, which is clearly better defined in HEC GeoRAS. As shown in Figure 7-15, there is a clearer distinction of where the water intersects the terrain, creating better graphical representations of flood delineation.

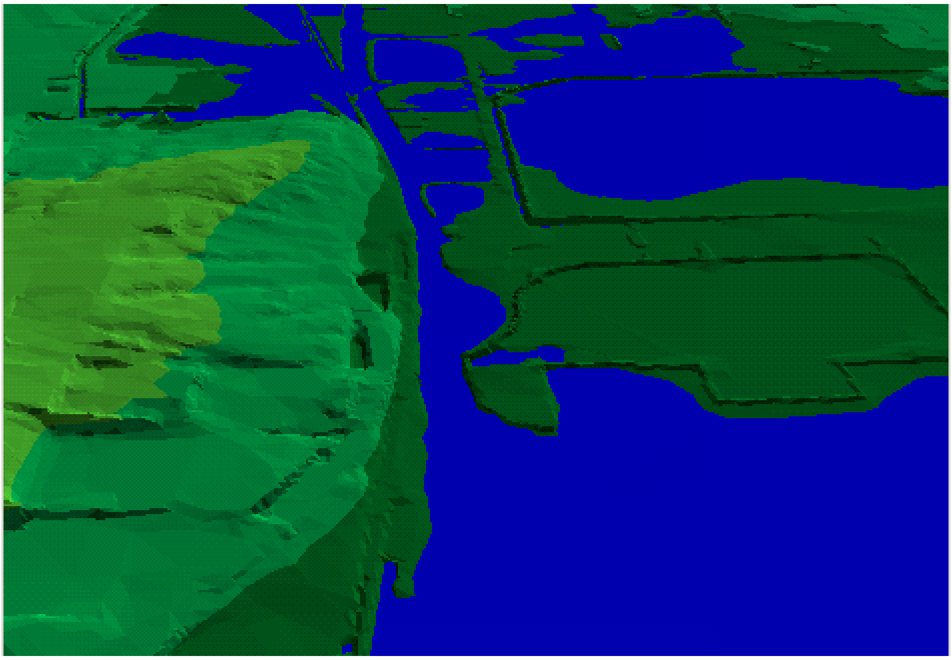


Figure 7-15. The view shows the distinction between water and terrain using TIN-based surfaces in HEC GeoRAS. The maximum water surface elevation developed from the HEC RAS model of the PDC study area is shown.

Chapter 8: Results and Conclusions

This chapter discusses the overall results of the research and the conclusions leading from the application of the two unsteady flow models. The analysis focuses on the applicability of the unsteady models and their connectivity with the spatial GIS environment.

8.1 Model Results

The limited number of gage stations in the Mill Creek watershed (one existing station for the entire watershed) led to both flow models not being properly calibrated. The accuracy of each model could not be validated. Without the model validation, this study's results can be analyzed qualitatively to assess the efficiency of flood modeling technologies.

The significance of flood visualization is the ability to portray a model's results to community members, planners, and officials in a way that is understandable to everyone. Unlike the steady flow models, the unsteady flow models can portray the effects of flood duration, which also have an important role in flood prevention planning. The model results section of this chapter summarizes the results of the models used in the study, and compare the results to steady flow modeling.

8.1.1 MIKE 11 Model Results

Importing water surface elevations derived from the MIKE 11 model into Arcview GIS was accomplished effortlessly since the stream network was accurately geo-referenced to the terrain model. The flood delineation process was faster using MIKE 11 GIS than using the HEC GeoRAS extension. The MIKE 11 GIS delineation process finds the difference between the water surface elevation and the ground elevation for each grid cell in the model. The delineation is accomplished using inverse distance-weighted interpolation from known water surface *points* (known as *h-points*) located at the center of each cross-section along the stream network, whereas the TIN-based delineation (used for the HEC RAS model) interpolates using 3-D water surface *lines* along the extent of each cross-section. One would presume that the HEC GeoRAS interpolation method would achieve more accurate results, because the flood plain was delineated using two surfaces (the terrain model and water surface TIN coverages) instead of by interpolation based on one *h-point* elevation value at each cross-section, as in the case for MIKE 11 GIS.

Surveyed data is the most accurate stream geometry data source. Using surveyed cross-section data in the flow model removes the iterative stream geometry extraction process required for the HEC RAS model. Unfortunately, the HEC-2 surveyed data did not cover the entire flood plain. An example is shown in Figure 8-1. The maximum water stage heights for the 25-yr storm event were well above the stream banks, and in some cases extended beyond the flood plains as well.

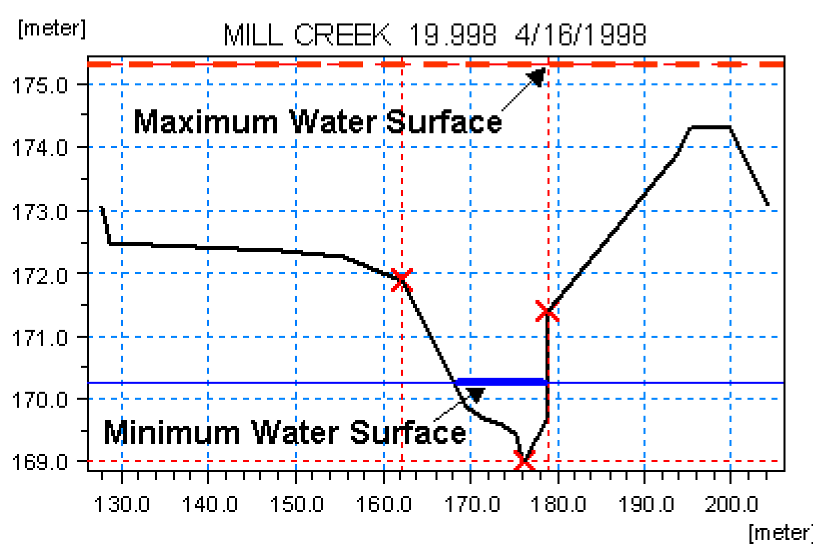


Figure 8-1. The horizontal, red dotted line above the cross-section at Chainage 19.998 is the maximum water surface at that location for the MIKE 11 model. In this case, the model does not account for the total conveyance in the flood plains.

Since the extent of the surveyed cross-sections was limited, the MIKE 11 model's flow characteristics did not account for the entire flood plain resistance or flood conveyance that actually occurs. This resulted in higher maximum water surface elevations and shorter flood durations than for the HEC RAS model. To improve the MIKE 11 model, the stream geometry data could be extracted from the terrain model, as was accomplished with the HEC RAS model. Another option is to re-survey the cross-sections to expand the left and right flood plains for each cross-section. Obviously the second option would be a more costly alternative.

An issue with the MIKE 11 model is the use of grid-based coverages (terrain model and water surface) in MIKE 11 GIS. An advantage to the grid-based method is it minimizes the use of computer memory and processing. The limitation to grid-based models, especially for smaller study areas, is the intersection of the terrain model and water surface coverages does not accurately represent flood delineation as well as using TIN-based coverages (this is discussed in Chapters 6 and 7). Based on this study, the MIKE 11 GIS post-processing tool (known as the *Flood Management* tool) is not the optimum choice for a study area with the size of the Primary Damage Center, which has an area of approximately 13.5 km^2 (5 km in length by 2.7 km in width). The MIKE 11 GIS post-processing tool would provide better images of flood delineation for study areas larger than the Primary Damage Center, where resolution becomes less important as area increases.

An advantage of the MIKE 11 model is its graphical user interface. Editing data is simple and easy to accomplish. The interface provides graphical representations for the geometric data and the time-series boundary conditions. Instead of creating a separate GIS export file for the MIKE 11 GIS post-processor, the interface automatically connects the GIS spatial data to the hydraulic model results. This is accomplished by the interconnectivity of the river network file to the flow model and the terrain model. As long as the XY-coordinates of the MIKE 11 river network file correspond to the terrain model coordinates, the flow data is easily imported and delineated.

Once the flow model results are imported into MIKE 11 GIS, the user effortlessly develops 2-D and 3-D flood map animations directly from Arcview GIS. The process eliminates the need to obtain screen captured images and subsequently copy them into an external animation software tool to accomplish the task as required by HEC GeoRAS.

8.1.2 HEC RAS Model Results

The HEC RAS model's stream geometry data is extracted from the terrain using the HEC GeoRAS extension. This difference in the two modeling methods is significant to flood visualization results. Unlike the MIKE 11 model, the stream cross-sections were extended beyond the extent of overbank flows, ensuring the flood plain's bed resistance covered the entire flow in the model. Unlike the HEC RAS model, the overall flood plain conveyance is not accounted for in the MIKE 11 model results. The HEC RAS model's overall flooding extent was less than what was found in the MIKE 11 model. Lower maximum water surface elevations and longer flood durations as compared to the MIKE 11 model were also observed.

A significant difference in flood visualization for the two models was also noticed. The TIN-based delineation method creates a more realistic delineation of flood levels from the terrain model. The TIN-based delineation works well for smaller study areas because of its high resolution, but can become cumbersome as the study area increases. The initial TIN-based terrain model of the Primary Damage Center (*Crtin1*) developed from the 1-ft contour data was cumbersome to use, because its TIN mesh consisted of 6,028,127 triangles (240 MB of computer memory capacity). Loading the *Crtin1* file into an Arcview GIS view takes 3-5 minutes to accomplish. Using 2-ft contours to develop the terrain model (*Nwtin1*) resulted in the new model loading quicker (less than 10 seconds) than the initial terrain model because the TIN mesh consists of 134,470 triangles (4.39 MB of computer memory capacity) – a significant decrease in computer memory and processing requirements. The water surface TIN developed in HEC GeoRAS was not an issue regarding computer memory and processing, since the TIN mesh contained around 500 triangles for each water surface developed. Obviously the processing is dependent on the data sources used to develop the terrain model, computer speed and capacity, and what accuracy the modeler expects for his or her results.

A limitation to the HEC GeoRAS model is the requirement to pre-process, or extract, stream geometry data from the terrain model to develop flood visualization images. There is no certainty that independent stream cross-sections can perfectly fit a terrain model accurately. If some or all of the cross-sections can be accurately geo-referenced to the terrain model, then the option to extract or not extract cross-sections from the terrain should be provided to the modeler. For flood visualization, an accurate depiction of the stream channel is of greater importance for the hydraulic model than for the terrain model. Most flood event models focus on the flow *above* the stream channel, so if the hydraulic model contains the best geometric data of the stream and flood plains, and the terrain model contains the best ground surface elevation beyond the stream channel, then the visualization tool should be valid. But when using HEC GeoRAS, pre-processing is necessary because the stream geometry data used in HEC RAS can only be extracted from the terrain model for ultimately developing flood maps in the HEC GeoRAS post-processor. The HEC GeoRAS interface should provide the pre-processing step as an option, not a requirement, to its users.

Some difficulties lie in importing GIS data from the terrain model into the HEC RAS geometry data editor. When data is unavailable, the HEC GeoRAS iterative process can derive cross-sections for a stream network from a terrain model in an area that has no cross-section data available. Sometimes the data exported into HEC RAS does not always import accurately. This occurs near junction locations (where tributaries connect with the main stream in the stream network). For this study, cross-section directions were occasionally reversed near junctions when imported from HEC GeoRAS preprocessor into the HEC RAS geometry data editor, not allowing the HEC RAS unsteady flow option to run properly. An example is shown in Figure 8-2. When this problem arises, the direction of the cross-section cut lines in the HEC GeoRAS pre-processor can first be verified and flipped as necessary, using the *Flip Polyline* command. If that is not the problem, then the cross-section's direction can be reversed in the geometry data editor in the HEC RAS interface, using the *Move Object* command.

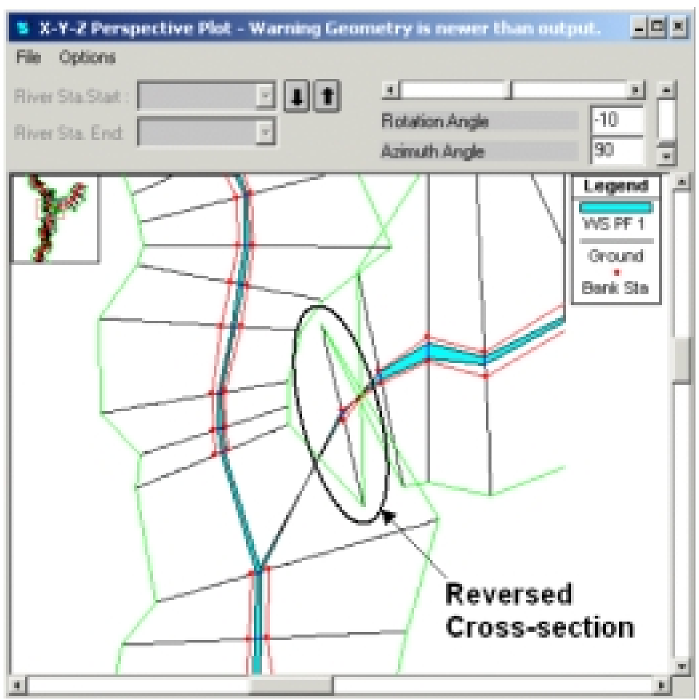


Figure 8-2. An example of a reversed cross-section shown in an XYZ plot in HEC RAS. Importing GIS data from HEC GeoRAS will occasionally reverse cross-section orders near junctions.

An advantage to using the HEC GeoRAS post-processing for flood delineation is the development of high resolution images for small areas (like the PDC study area). The TIN-based delineation method creates clearer flood map images as compared to the MIKE 11 grid-based delineation method. A disadvantage to the TIN-based method is the increase in computer processing time and computer memory requirements.

Flood delineation in the HEC GeoRAS post-processor is simple, but animation processing is tedious. When reading a GIS export file created from the HEC RAS model results, the HEC GeoRAS post-processor truncates the name of the data file for each time step. When this occurs, the water surfaces created for the different time steps cannot be differentiated by the computer, as shown in Figure 8-3. To resolve this problem, water surface profiles for individual time steps were imported as separate GIS export files into HEC GeoRAS. This procedure required numerous GIS export file development iterations from the HEC RAS interface. Once accomplished, each time step was copied with a screen captured image and pasted into an animation software tool to develop an animated GIF of the flood event.

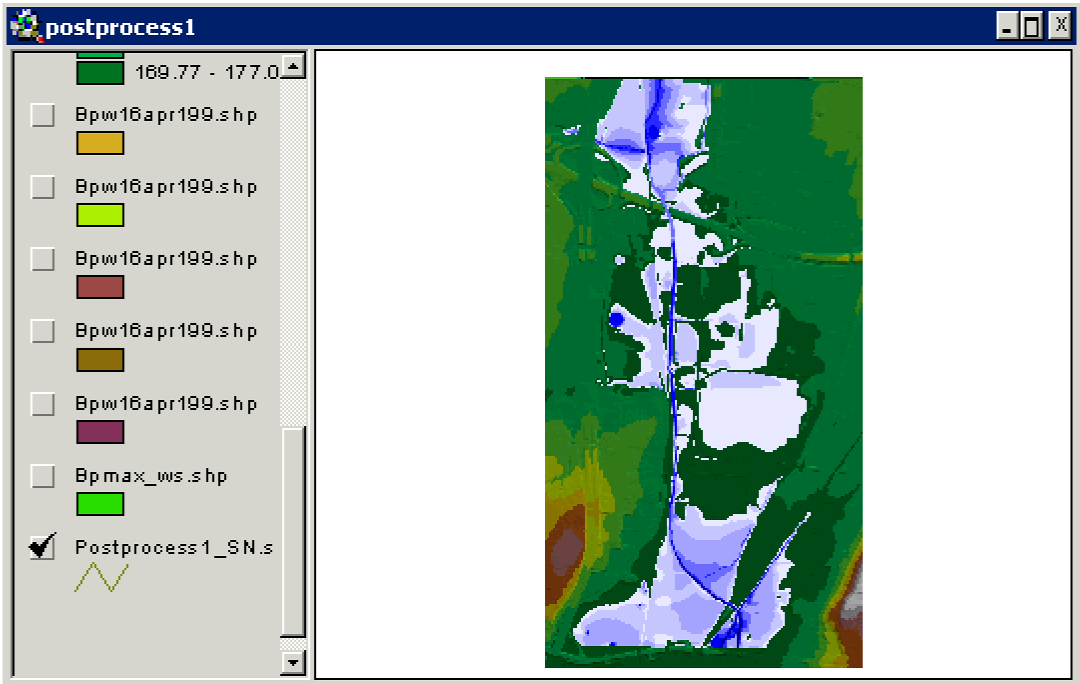
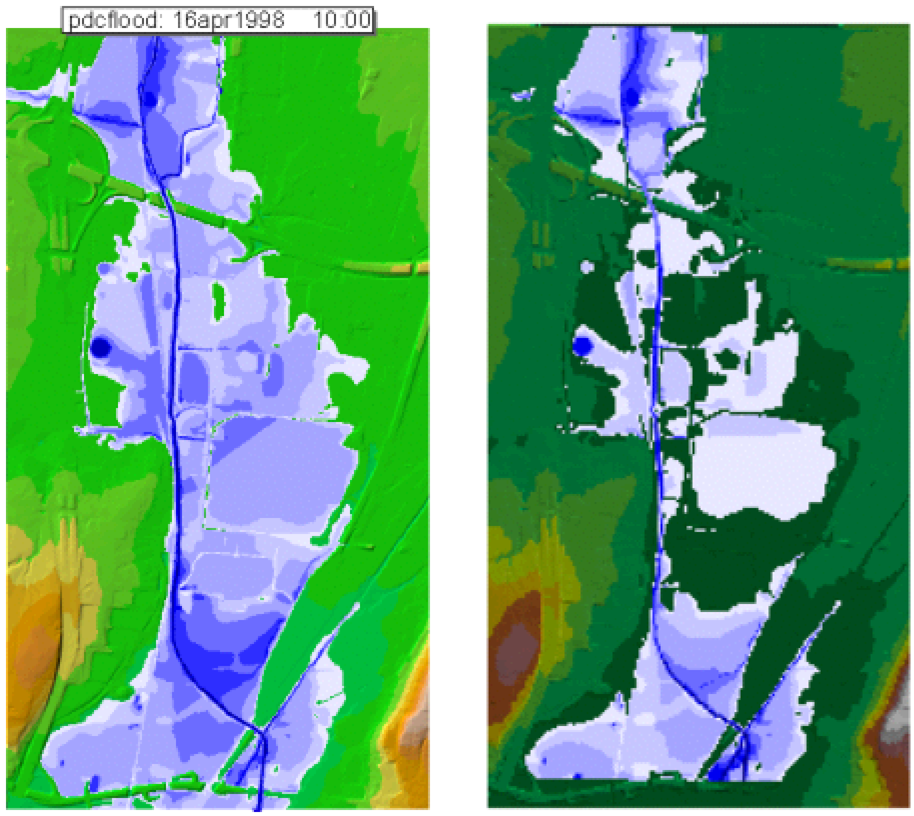


Figure 8-3. The Arcview GIS view shows the polygon themes (called "Bpw16apr199.shp") in the legend imported from the HEC RAS flow model for different time steps. Each polygon theme was imported with the same name, thus Arcview GIS could not differentiate between the different time steps.

8.1.3 Comparison of the Unsteady Flow Model Results

As previously discussed, a significant difference occurred with maximum flood stage, time of peak stage, and flood duration for the two flow models. The time of the peak stage differed by 3 hours, occurring at 08:32 am for the MIKE 11 model and 11:00 am for the HEC RAS model. The HEC RAS model's flow attenuated more rapidly, with a lower maximum stage height and a longer flood duration. The MIKE 11 model did not attenuate as quickly, resulting in a higher maximum stage height and shorter flood duration.



(a) **(b)**

Figure 8-4. A visual comparison is shown of the maximum stage heights for (a) the MIKE 11 model and (b) the HEC RAS model.

Extracting the stream geometry data from the terrain model for the HEC RAS model initially did not seem important, since overbank flow is usually the focus for flood analysis. But the survey cross-section data did not accommodate the extent of inundation in the flood plains. An example of the difference in the HEC RAS and MIKE 11 model cross-sections are shown in Figure 8-4. Adding the flood plain extents to the HEC RAS model affected the model results in three ways: 1) maximum stage was reduced, 2) flood duration increased, and 3) the time of peak stage was delayed. The factor causing the changes to the two models is the inclusion of the flood plain conveyance to the overall flow. Since the flood plains are limited in the MIKE 11 model, the results are a higher maximum stage, a more rapid time of peak, and a shorter flood duration.

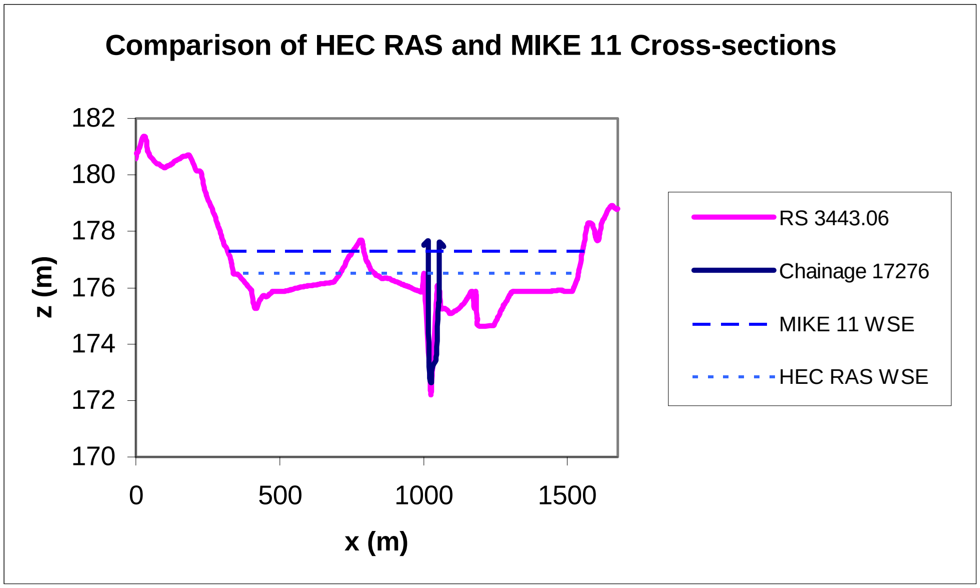


Figure 8-5. The MIKE 11 (in dark blue) and HEC RAS (in red) cross-sections shown are approximately 12 meters from each other along the stream network. The total flood plain conveyance is accounted for in the HEC RAS model, significantly slowing down flow as compared to the MIKE 11 model results. The figure also depicts the maximum water surface elevations for the MIKE 11 (dashed line) and HEC RAS (dotted line) models, which are affected by the flood plain conveyance included or not included in the model(s).

8.1.4 Comparison to Steady Flow Modeling

An additional analysis of the study area was conducted using the HEC RAS steady-state model to compare steady flow modeling to unsteady flow modeling. When using a steady flow model, most modelers consider the peak runoff flows at the boundary conditions for a specified storm event, resulting in water stage height being significantly higher than one for the unsteady flow model. This occurs because the steady flow model does not account for the timing differences in the runoff hydrograph rainfall responses into the system, the differences being depicted in Table 8-1. Figure 8-6 is provided to understand the relation of the contributing runoff from the watersheds. Using the peak runoff flows for storm events in a steady flow model will result in over design.

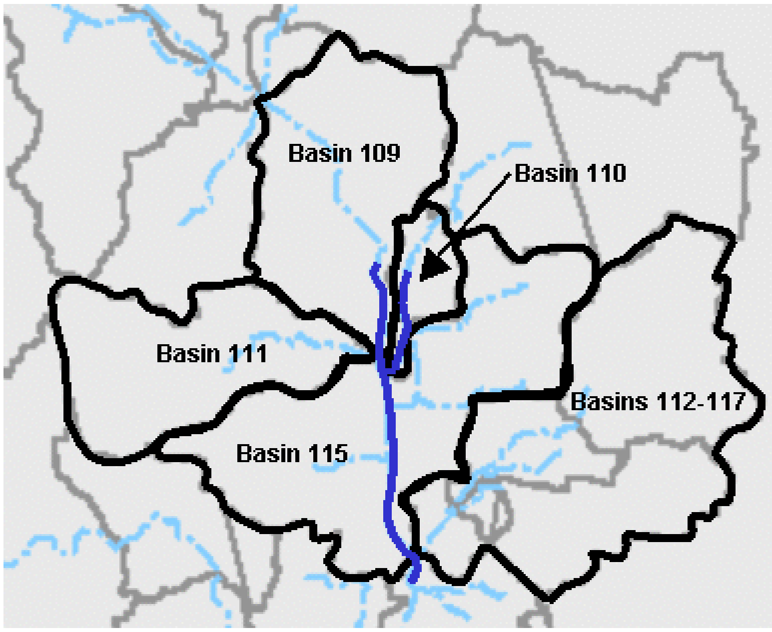


Figure 8-6. Schematic of the watersheds contributing runoff to the Primary Damage Center. The extent of the hydraulically modeled stream system is bolded in blue. Any upstream watersheds contributing flow into this portion of the streams is accounted for in the upstream boundaries.

Table 8-1. Time of peaks for the PDC study area boundary conditions.

Boundary Condition	**Peak Value**	**Time of Peak**
Mill Creek		
Upstream flow boundary	97.069 m^3/s	08:56 am
Basin 109 runoff	32.505 m^3/s	08:00 am
Basin 110 runoff	6.236 m^3/s	07:45 am
Basin 111 runoff	26.565 m^3/s	07:45 am
Basin 115 runoff	43.274 m^3/s	08:15 am
Basins 112-117 runoff	34.615 m^3/s	06:45 am
Downstream stage boundary	174.24 m	08:32 am
East Fork		
Upstream flow boundary	53.347 m^3/s	07:45 am
HEC RAS Unsteady Flow Model		11:00 am
MIKE 11 Unsteady Flow Model		08:32 am

A comparison of the maximum stage height of the steady and unsteady HEC RAS flow models is shown in Figure 8-7. Based on this comparison, the unsteady flow model provides two significant points to consider for future design and modeling. For most cases, the unsteady flow model will provide a maximum water stage height less than the stage height found from the steady flow model since most steady flow models consider the peak discharges as occurring simultaneously everywhere, which may not peak at the same time. Secondly, the unsteady flow model also considers flood duration as a factor in flood analysis. Real property can significantly be affected by the difference in time of inundation.

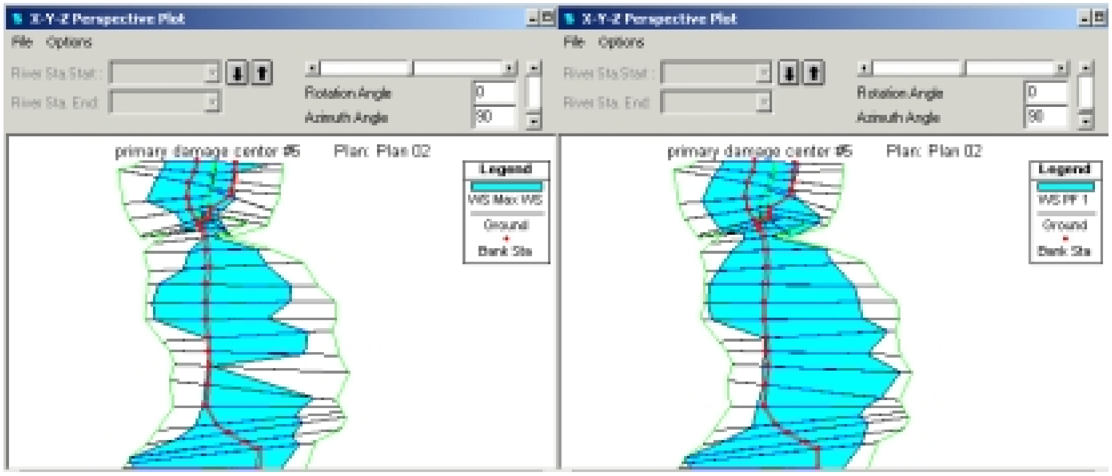
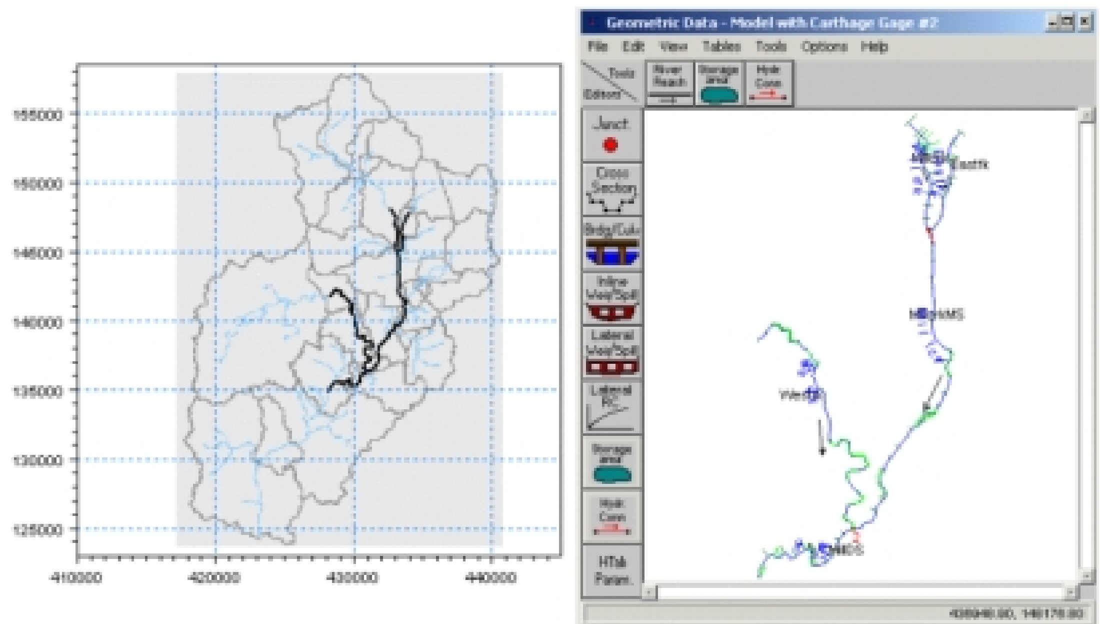


Figure 8-7. Comparison of maximum water surfaces for the HEC RAS unsteady flow model (on the left) and the steady model (on the right) for the 25-yr storm event. Because of timing differences in peak flows, the steady flow results show a greater portion of inundation for the PDC study area.

8.2 Conclusions

Using unsteady flow models to develop flood visualizations is complicated and lengthy, depending on the size of the study area. Many factors can affect the results, especially if the data sources are inaccurate or incomplete. The amount of stream geometry data can become very substantial as the size of the stream network increases. It is best to choose a modeling method that best accommodates the processing of the geometry data.

Many factors become problematic in the model developing process for unsteady flow models that are not an issue for steady flow models. The best approach is to initially gain an understanding of how the unsteady flow algorithm(s) work, and obtain some experience working with existing unsteady flow models. For this study, development of the MIKE 11 model was the initial focus. After approximately six months of HEC-2 and HEC HMS data conversions, understanding the nuances of unsteady flow, and resolving errors with the flow simulation, a MIKE 11 hydraulic model was developed for approximately 17.3 kilometers of Mill Creek, with two branching streams. The HEC RAS model was easier to develop, since the unsteady flow learning curve was minimized during the MIKE 11 model development, and the HEC-2 and HEC HMS data was easier to incorporate into the HEC RAS model. A model similar to the MIKE 11 model using the HEC RAS interface was developed within two weeks. Once the terrain model was created, the process of developing flood maps with the MIKE 11 GIS and HEC GeoRAS extensions was simple.



(a) **(b)**

Figure 8-8. Schematics of the initial hydraulic models developed in (a) MIKE 11 and (b) HEC RAS. The initial models covered over 17.3 kilometers of Mill Creek as well as two additional branching streams.

The unsteady flow algorithms are not as mathematically stable as steady flow models. When a water stage height is calculated at a value less than the streambed elevation, the flow simulation crashes. This calculation may be mathematically accurate. Natural systems do not always follow the rules of mathematics. In such cases, additional cross-sections may be added to the model, which decreases the incremental step in the stage difference from element to element in the system. Another option is to decrease the model's simulation time step, as was the case for this study. 10 and 30-minute time steps were initially used for both the MIKE 11 and HEC RAS models, leading to both models crashing. A 4-minute time step was the optimum time increment used for both models.

The unsteady flow model has the powerful capability to model the characteristics of watershed runoff responses from a storm event over time. This makes flood animations more accurate than for those created from steady flow models. To minimize data processing, it is recommended to use an unsteady flow model that can import results from a linked hydrologic model. The process of importing the runoff hydrographs from the HEC HMS model into the HEC RAS model was simple because of the DSS utility. Exporting the HEC HMS model results into the MIKE 11 interface was not easy to accomplish. The Danish Hydraulic Institute has created a hydrologic model, called *NAM*, which the MIKE 11 model can be linked to.

The final point to consider in unsteady flow model applications in Arcview GIS is the depiction of the flood delineated from the terrain model. A lot of research has been conducted on how to integrate separate data sources into one modified terrain model to show accurate flood maps and visualizations. Since flood visualization looks at flow over the stream bank, the concern should not be for the stream channel, but for what occurs in the flood plains. If the terrain data is accurate (as was the case for this study), then inclusion of surveyed stream geometry into the terrain model may not be necessary. As found within this study, the surveyed stream geometry data could not accommodate the flow derived from the 25-yr storm event, thus the terrain model was necessary for developing the stream geometry data, as in the case of the HEC RAS model.

8.2.1 Unsteady Flow Model Advantages and Limitations

When applying the two methodologies of unsteady flow to the same study area, it was difficult to determine which model was more advantageous to use. Both methods use unsteady flow algorithms that are valid and widely accepted techniques used in the United States and abroad. This section summarizes the quality-based findings when using both modeling methodologies; most points being previously addressed in this report. The purpose of compiling the key points from this research is to provide future unsteady flow modeling a better approach to save on time and resources.

The MIKE 11 Model

Advantages

- The interface is easy to use. Editing is simple and easy to accomplish.
- The conversion of flood map to 2-D and 3-D animations in Arcview GIS requires no additional animation software.

Limitations

- The software package is expensive, currently running approximately 6,000 U.S. dollars.
- The software is currently limited to using metric units. Chainage values can only be inputted in units of meters.
- The Grid-based surfaces used by MIKE 11 GIS depict a jagged flood plain boundary where the water stage is delineated from the terrain. Graphical images of smaller study areas, that require a higher resolution image, are affected more than larger study areas.
- The stream network referencing method for the MIKE 11 model starts from the most upstream location and increases as you move downstream (Chainage values). Not all upstream stream sources can easily be defined to begin at a specific location.

- Since the MIKE 11 model is not yet widely used in the United States, current U.S. hydraulic model data are not easily imported into the interface.

The HEC RAS Model

Advantages

- The HEC RAS software is available to anyone over the internet.

- The River Station stream network referencing method accommodates both U.S. customary units and metric units. The referencing method starts from the most downstream location of the stream and increases as you move upstream, unlike the MIKE 11 model. This method is easier to define since the most downstream location of a stream is easy to spatially define.

- The HEC RAS model accommodates either U.S. customary units or metric units for all values defined in the model.

- Existing HEC-2, HEC RAS, and UNET flow model data are easily imported into the HEC RAS interface.

- The TIN-based surfaces used in the HEC GeoRAS post-processor depict more accurate looking flood delineations, regardless of study area size.

Limitations

- The development of flood animations from HEC GeoRAS requires additional animation software. The process of obtaining screen captures and including the images into an animation software interface is tedious and time consuming.

- Modelers are forced to use the stream geometry data extraction pre-processing in HEC GeoRAS to ultimately use the post-processing visualization tools. Even when surveyed data is accurate and geo-referenced by the stream network, the geometry extraction from the terrain model is still required.

8.2.2 Future Work

As for most flow visualization techniques, additional modifications to the existing model can still be improved upon for future studies. Adding the man-made structures within the study area into the terrain model would affect the overall results of the unsteady flow models. Azagra (1999) developed a method to include the buildings into a TIN-based terrain model. If using the HEC GeoRAS pre-processor, buildings and structures can be incorporated into the flow model's geometric data.

Another improvement to the current model is the inclusion of bridges and other hydraulic structures into the flow model. The PDC study area has eight bridges (roadway and railway bridges) that have not been added to the flow model. The integration of the bridges into the model would be simpler for HEC RAS since the bridge data can be obtained from HEC-2 files. Based on the modeled characteristics of the study area's flood plains, adding bridges into the model would amplify flood inundation through backwater effects from piers and abutments. The bridges would require extensive analysis to determine an optimum modeling method for high (flow over the bridge's roadway) or low (flow under the bridge's roadway) bridge flows (Bonner, 2000).

Appendix A: MIKE 11 Chainage - HEC-2 River Station Conversions

The cross-section data for this study was initially available as a HEC-2 geometry file. The file was imported into HEC RAS, and converted into a text file readable by the MIKE 11 software. Unfortunately, the river network referencing for HEC RAS and MIKE 11 required two conversions:

1) Movement of the initial point of reference from the most downstream location (HEC RAS) to the most upstream location (MIKE 11)
2) The conversion of units of feet (HEC-2 files) to units of meters (MIKE 11)

This was accomplished by developing a spreadsheet for the conversion of the initial HEC-2 River Stations to MIKE 11 Chainages. The Chainage values in the MIKE 11 model were inputted manually from the spreadsheet results. MIKE 11 Chainages values were initially based on a stream network for the entire extent of Mill Creek.

Table A-1. HEC-2 River Station conversion to MIKE 11 Chainages

HEC-2 River Stations (ft)	Downstream Length (ft)	Downstream Length (m)	MIKE 11 Chainages (m)
Mill Creek			
200332	292	89.00	15779
200040	1220	371.86	15496
198820	1130	344.42	15868
197690	960	292.61	16213
Interpolated Cross-section at the confluence of East Fork into Mill Creek			16401.453
196730	730.00	222.50	16505
196000	170.00	51.82	16728
195830	60.00	18.29	16780

HEC-2 River Stations (ft)	Downstream Length (ft)	Downstream Length (m)	MIKE 11 Chainages (m)
195770	150.00	45.72	16798
195620	10.00	3.05	16844
195610	210.00	64.01	16847
195400	170.00	51.82	16911
195230	365.00	111.25	16962
194865	550.00	167.64	17074
194315	275.00	83.82	17241
194040	620.00	188.98	17325
193420	2320.00	707.14	17514
191100	200.00	60.96	18221
190900	1285.00	391.67	18282
189615	865.00	263.65	18674
188750	340.00	103.63	18938
188410	410.00	124.97	19041
188000	500.00	152.40	19166
187500	350.00	106.68	19319
187150	1290.00	393.19	19425
185860	590.00	179.83	19818
185270	230.00	70.10	19998
185040	500.00	152.40	20068
184540	610.00	185.93	20221
183930	220.00	67.06	20407
183710	15.00	4.57	20474

HEC-2 River Stations (ft)	Downstream Length (ft)	Downstream Length (m)	MIKE 11 Chainages (m)
183695	95.00	28.96	20478
183600	20.00	6.10	20507
183580	320.00	97.54	20513
183260	925.00	281.94	20611
182335	0.00	0.00	20732.45
East Fork			
1246.63	169.16	51.56	11296
1077.47	190.50	58.06	11465
886.97	185.93	56.67	11656
701.04	390.14	118.91	11842
310.90	310.90	94.76	12232
0.00	25.00	7.62	12543
-25.00	0.00	0.00	12550

Appendix B: Visual Fortran Program used for Cross-section Data Conversion

Prepared by
Stefan Szylkarski
Danish Hydraulic Institute
11 October 1999

```
Content-Type: application/octet-stream;

        name="HEC2M11.for"

Content-Transfer-Encoding: 7bit

Content-Disposition: attachment;

        filename="HEC2M11.for"


        PROGRAM hec2m11


C       **********************************************

C       Program reads HEC-RASv2.1 GO1 files and extracts cross

C               section information and write to MIKE11 inport text file.

C               IMPORTANT:-  Please check all cross sections converted.

C       Errors may occur as the program has not

C       been fully tested.

C

C       Stefan Szylkarski - Danish Hydraulic Institute

C       - sps@dhi.dk
```

```
C       - 11 October 1999
C                                   *********************************************

        CHARACTER*8  chain
        CHARACTER*50 fin,fut
        CHARACTER*80 line

        REAL*4      xz(20,10)
        INTEGER*2   npts

c**     Open Files

        WRITE(*,'(" HECRAS G01 File name? : "\)')
        READ(*,'(A)') fin

        WRITE(*,'(" M11 Output file name? : "\)')
        READ(*,'(A)') fut
        WRITE(*,'(/)')

        OPEN (UNIT=10, FILE=fin)
        OPEN (UNIT=20, FILE=fut)

c********Search for Chainage Lines
```

```
10      CONTINUE

        READ (10,'(A80)',END=9000) line

        IF ( line(1:7) .EQ. 'Type RM' ) THEN
11      chain = line(28:35)
12      READ (10,'(A80)',END=9000) line

c********Search for Station Elevation lists associated with chainage

        IF (line(1:9) .EQ. '#Sta/Elev' ) THEN
        READ(line(12:14),'(I3)') npts
        ELSEIF( line(1:7) .EQ. 'Type RM' ) THEN
        GOTO 11
        ELSE
        GOTO 12
        ENDIF
        ELSE
        GOTO 10
        ENDIF

c********Read up the cross section X,Z pairs
```

```
      nrows = ANINT((REAL(npts) / 5.0 ) + 0.5)

      DO I = 1, nrows
      IF ( I.EQ.nrows) THEN
      nvals = (npts - (nrows-1)*5)*2

      ELSE
      nvals = 10

      ENDIF
      READ(10,*) (xz(i,j),j=1,nvals)
      ENDDO

c**   WRITE out Cross Section in Mike11 format

      WRITE(20,'("HECRAS")')
      WRITE(20,'("RIVER1")')
      WRITE(20,'(14X,A8)') chain
      WRITE(20,'("COORDINATES")')
      WRITE(20,'(4X,"0")')
      WRITE(20,'("FLOW DIRECTION")')
      WRITE(20,'(4X,"0")')
```

```
      WRITE(20,'("DATUM")')
      WRITE(20,'(6X,"0.000")')
      WRITE(20,'("RADIUS TYPE")')
      WRITE(20,'(4X,"0")')
      WRITE(20,'("DIVIDE X-Section")')
      WRITE(20,'("0")')
      WRITE(20,'("PROFILE",9X,i3)') npts
      n = 0
      DO K = 1,nrows
      DO L = 1,5
      n = n+1
      IF (n .LE. npts ) THEN
      WRITE(20,30) xz(k, (l*2)-1 ),xz(k,l*2)
30    FORMAT(3X,F7.2,4X,F6.2,6X,'1.00')
      ENDIF
      ENDDO
      ENDDO
      WRITE(20,*)'******************************'

      GOTO 10
9000  CONTINUE
      STOP
      END
```

Appendix C: MIKE 11 Cross-section File

The MIKE 11 cross-section file data is read as input in column form. Each cross-section is identified with a TOPO identification number, branch identification, and Chainage number. The TOPO identification differentiates different cross-section to be processed during the simulation. A default TOPO identification number of 100 was used for the entire river network. Interpolated cross-sections are identified with a "1" value. In the profile data, the first two columns are the X and Z coordinates for the cross-section. The third column is the local resistance factor for each cross-section, and is multiplied by the global resistance factors in the hydrodynamic file (the default being 1). The fourth column identifies the differentiates the stream channel from the flood plains. The number 1 identifies the left bank, 2 identifies the stream bed, and 3 identifies the right bank.

```
100
East Fork
           11427.124
COORDINATES
    0
FLOW DIRECTION
    0
DATUM
      0.00
RADIUS TYPE
    0
DIVIDE X-Section
0
SECTION ID

INTERPOLATED
    1
ANGLE
    0.00
PROFILE        37
      4.51    182.06      1.00     <#0>
      7.44    181.57      1.00     <#0>
      8.69    181.09      1.00     <#0>
     10.43    180.61      1.00     <#0>
     16.55    179.64      1.00     <#0>
```

```
     19.72    179.15      1.00     <#0>
     23.31    178.66      1.00     <#0>
     29.05    178.16      1.00     <#0>
     35.13    177.95      1.00     <#0>
     44.72    177.61      1.00     <#0>
     57.69    177.53      1.00     <#0>
     58.50    177.51      1.00     <#1>
     58.50    177.48      1.00     <#0>
     59.49    176.86      1.00     <#0>
     62.01    175.00      1.00     <#2>
     66.68    175.00      1.00     <#0>
     67.23    175.11      1.00     <#0>
     67.34    175.13      1.00     <#0>
     69.46    176.23      1.00     <#0>
     69.97    176.43      1.00     <#0>
     71.67    176.99      1.00     <#0>
     73.14    177.55      1.00     <#3>
     73.42    178.27      1.00     <#0>
     76.31    178.68      1.00     <#0>
     80.64    178.21      1.00     <#0>
     86.90    177.74      1.00     <#0>
    119.09    177.89      1.00     <#0>
    124.11    177.30      1.00     <#0>
    151.12    177.16      1.00     <#0>
    163.65    177.35      1.00     <#0>
    163.92    177.49      1.00     <#0>
    165.04    178.11      1.00     <#0>
    185.61    177.84      1.00     <#0>
    199.02    177.97      1.00     <#0>
    202.54    178.07      1.00     <#0>
    223.68    178.54      1.00     <#0>
    240.79    178.54      1.00     <#0>
*******************************
100
East Fork
           11465.000
COORDINATES
    0
FLOW DIRECTION
    0
DATUM
      0.00
RADIUS TYPE
    0
DIVIDE X-Section
0
SECTION ID

INTERPOLATED
    0
ANGLE
    0.00
```

```
PROFILE        24
      0.00    182.88      1.00     <#0>
      3.14    182.27      1.00     <#0>
      4.48    181.66      1.00     <#0>
      6.34    181.05      1.00     <#0>
     12.89    179.83      1.00     <#0>
     16.28    179.22      1.00     <#0>
     20.12    178.61      1.00     <#0>
     26.27    178.00      1.00     <#0>
     43.04    177.39      1.00     <#0>
     57.79    177.39      1.00     <#1>
     57.79    177.36      1.00     <#0>
     58.64    176.78      1.00     <#0>
     60.81    174.96      1.00     <#2>
     65.87    174.96      1.00     <#0>
     68.37    176.17      1.00     <#0>
     69.98    176.78      1.00     <#0>
     71.38    177.42      1.00     <#3>
     74.46    178.00      1.00     <#0>
     78.67    177.39      1.00     <#0>
     84.76    176.78      1.00     <#0>
    180.78    177.39      1.00     <#0>
    197.24    178.00      1.00     <#0>
    217.81    178.61      1.00     <#0>
    234.45    178.61      1.00     <#0>
*******************************
100
East Fork
           11656.000
COORDINATES
    0
FLOW DIRECTION
    0
DATUM
      0.00
RADIUS TYPE
    0
DIVIDE X-Section
0
SECTION ID

INTERPOLATED
    0
ANGLE
    0.00
PROFILE        22
      0.00    179.83      1.00     <#0>
      0.18    179.22      1.00     <#0>
     24.87    178.61      1.00     <#0>
     27.95    178.00      1.00     <#0>
     29.08    177.39      1.00     <#1>
     30.45    176.78      1.00     <#0>
```

```
     31.30    176.17      1.00     <#0>
     32.77    175.57      1.00     <#0>
     37.92    174.44      1.00     <#2>
     39.53    175.57      1.00     <#0>
     41.15    176.17      1.00     <#0>
     42.00    176.78      1.00     <#0>
     44.32    178.00      1.00     <#3>
     44.50    178.03      1.00     <#0>
     47.27    178.61      1.00     <#0>
     51.66    178.61      1.00     <#0>
     55.02    177.39      1.00     <#0>
     65.01    176.78      1.00     <#0>
    132.47    176.78      1.00     <#0>
    218.05    176.78      1.00     <#0>
    249.75    178.00      1.00     <#0>
    263.29    178.00      1.00     <#0>
*******************************
100
East Fork
           11842.000
COORDINATES
    0
FLOW DIRECTION
    0
DATUM
      0.00
RADIUS TYPE
    0
DIVIDE X-Section
0
SECTION ID

INTERPOLATED
    0
ANGLE
    0.00
PROFILE        16
      0.00    179.83      1.00     <#0>
      0.12    178.61      1.00     <#0>
      0.49    178.00      1.00     <#0>
     12.13    177.39      1.00     <#0>
     25.48    176.69      1.00     <#1>
     26.55    176.17      1.00     <#0>
     27.77    175.57      1.00     <#0>
     29.84    174.96      1.00     <#0>
     33.74    174.35      1.00     <#2>
     35.69    174.96      1.00     <#0>
     37.31    175.57      1.00     <#0>
     38.04    176.17      1.00     <#3>
     41.45    176.88      1.00     <#0>
     42.37    177.39      1.00     <#0>
     51.18    177.39      1.00     <#0>
```

```
     53.43    176.78      1.00      <#0>
*******************************
100
East Fork
           12232.000
COORDINATES
    0
FLOW DIRECTION
    0
DATUM
      0.00
RADIUS TYPE
    0
DIVIDE X-Section
0
SECTION ID

INTERPOLATED
    0
ANGLE
    0.00
PROFILE        10
      0.00    177.55      1.00      <#0>
     54.86    177.55      1.00      <#0>
     59.44    178.77      1.00      <#0>
     61.57    178.77      1.00      <#0>
     70.10    175.12      1.00      <#1>
     71.63    173.90      1.00      <#2>
     73.15    173.90      1.00      <#0>
     77.72    175.12      1.00      <#3>
     91.44    176.64      1.00      <#0>
    182.88    176.64      1.00      <#0>
*******************************
100
East Fork
           12534.439
COORDINATES
    0
FLOW DIRECTION
    0
DATUM
      0.00
RADIUS TYPE
    0
DIVIDE X-Section
0
SECTION ID

INTERPOLATED
    0
ANGLE
    0.00
```

```
PROFILE        8
      0.00    176.11      1.00     <#0>
     30.48    175.81      1.00     <#1>
     33.53    173.98      1.00     <#0>
     41.15    173.16      1.00     <#2>
     51.82    174.59      1.00     <#0>
     56.39    175.20      1.00     <#3>
     70.10    175.81      1.00     <#0>
     79.25    176.11      1.00     <#0>
*******************************
100
Mill Creek
           15407.150
COORDINATES
    0
FLOW DIRECTION
    0
DATUM
      0.00
RADIUS TYPE
    0
DIVIDE X-Section
0
SECTION ID

INTERPOLATED
    1
ANGLE
    0.00
PROFILE        62
     17.27    180.80      1.00     <#0>
     17.60    178.49      1.00     <#0>
     18.33    178.38      1.00     <#0>
     20.16    178.16      1.00     <#0>
     29.89    178.11      1.00     <#0>
     53.80    178.08      1.00     <#0>
     81.66    177.99      1.00     <#0>
     99.53    177.96      1.00     <#0>
    154.19    177.85      1.00     <#0>
    180.73    177.83      1.00     <#0>
    196.85    177.85      1.00     <#0>
    211.21    177.82      1.00     <#0>
    221.38    177.72      1.00     <#0>
    221.99    177.69      1.00     <#0>
    223.30    177.56      1.00     <#0>
    225.41    177.55      1.00     <#0>
    228.03    177.46      1.00     <#0>
    229.61    177.26      1.00     <#1>
    229.79    177.22      1.00     <#0>
    231.39    176.47      1.00     <#0>
    232.65    175.91      1.00     <#0>
    232.88    175.83      1.00     <#0>
```

```
    234.02    174.54      1.00     <#0>
    234.16    174.50      1.00     <#0>
    234.82    174.38      1.00     <#0>
    236.19    174.02      1.00     <#0>
    236.21    174.01      1.00     <#0>
    236.55    173.96      1.00     <#0>
    236.64    173.96      1.00     <#0>
    238.72    173.88      1.00     <#2>
    240.65    174.31      1.00     <#0>
    240.82    174.36      1.00     <#0>
    241.27    174.75      1.00     <#0>
    242.96    174.89      1.00     <#0>
    244.47    174.99      1.00     <#0>
    244.89    175.08      1.00     <#0>
    246.04    175.37      1.00     <#0>
    246.71    175.60      1.00     <#0>
    246.82    175.61      1.00     <#0>
    247.20    175.71      1.00     <#0>
    247.27    175.72      1.00     <#0>
    247.30    175.73      1.00     <#0>
    249.51    176.34      1.00     <#0>
    251.82    176.60      1.00     <#0>
    251.89    176.61      1.00     <#0>
    253.75    176.95      1.00     <#0>
    255.57    177.36      1.00     <#0>
    255.68    177.37      1.00     <#3>
    258.55    177.55      1.00     <#0>
    260.57    177.46      1.00     <#0>
    261.43    177.52      1.00     <#0>
    263.16    177.62      1.00     <#0>
    264.88    177.63      1.00     <#0>
    266.03    177.57      1.00     <#0>
    269.48    177.64      1.00     <#0>
    278.98    177.78      1.00     <#0>
    319.25    178.00      1.00     <#0>
    346.00    178.03      1.00     <#0>
    374.19    178.11      1.00     <#0>
    417.06    178.33      1.00     <#0>
    458.74    178.49      1.00     <#0>
    459.05    180.77      1.00     <#0>
*******************************
100
Mill Creek
           15496.000
COORDINATES
    0
FLOW DIRECTION
    0
DATUM
      0.00
RADIUS TYPE
    0
```

```
DIVIDE X-Section
0
SECTION ID

INTERPOLATED
    0
ANGLE
    0.00
PROFILE        27
      0.00    181.36      1.00     <#0>
      0.30    178.16      1.00     <#0>
    167.55    178.00      1.00     <#0>
    190.44    177.85      1.00     <#0>
    198.12    177.36      1.00     <#1>
    198.36    177.36      1.00     <#0>
    200.50    176.78      1.00     <#0>
    202.48    176.30      1.00     <#0>
    204.00    174.65      1.00     <#0>
    205.07    174.47      1.00     <#0>
    206.90    174.01      1.00     <#0>
    206.93    174.01      1.00     <#0>
    207.39    173.95      1.00     <#0>
    207.51    173.95      1.00     <#0>
    210.28    173.92      1.00     <#2>
    212.57    174.53      1.00     <#0>
    213.06    175.05      1.00     <#0>
    216.53    175.20      1.00     <#0>
    218.97    175.78      1.00     <#0>
    219.09    175.78      1.00     <#0>
    219.58    175.84      1.00     <#0>
    219.61    175.84      1.00     <#0>
    224.61    176.66      1.00     <#0>
    228.60    177.55      1.00     <#0>
    228.72    177.55      1.00     <#3>
    426.72    178.13      1.00     <#0>
    427.02    181.36      1.00     <#0>
*******************************
100
Mill Creek
           15868.000
COORDINATES
    0
FLOW DIRECTION
    0
DATUM
      0.00
RADIUS TYPE
    0
DIVIDE X-Section
0
SECTION ID
```

```
INTERPOLATED
    0
ANGLE
    0.00
PROFILE        12
      0.00    178.00      1.00     <#0>
      3.05    176.78      1.00     <#0>
     30.48    176.48      1.00     <#0>
    109.73    176.78      1.00     <#0>
    194.46    176.78      1.00     <#0>
    196.60    176.17      1.00     <#1>
    198.12    174.96      1.00     <#0>
    201.17    173.74      1.00     <#0>
    202.69    173.74      1.00     <#2>
    210.31    176.78      1.00     <#3>
    323.09    176.78      1.00     <#0>
    329.18    178.00      1.00     <#0>
*******************************
100
Mill Creek
           16213.000
COORDINATES
    0
FLOW DIRECTION
    0
DATUM
      0.00
RADIUS TYPE
    0
DIVIDE X-Section
0
SECTION ID

INTERPOLATED
    0
ANGLE
    0.00
PROFILE        12
    295.66    176.17      1.00     <#0>
    335.28    176.17      1.00     <#0>
    396.24    176.48      1.00     <#0>
    457.20    176.48      1.00     <#0>
    490.73    176.17      1.00     <#1>
    492.25    174.35      1.00     <#0>
    496.82    173.43      1.00     <#2>
    498.35    173.43      1.00     <#0>
    502.92    174.35      1.00     <#0>
    506.88    176.78      1.00     <#3>
    513.89    177.39      1.00     <#0>
    515.11    178.00      1.00     <#0>
*******************************
100
```

```
Mill Creek
           16728.000
COORDINATES
    0
FLOW DIRECTION
    0
DATUM
      0.00
RADIUS TYPE
    0
DIVIDE X-Section
0
SECTION ID

INTERPOLATED
    0
ANGLE
    0.00
PROFILE        9
      0.00    175.87      1.00     <#0>
     30.48    175.57      1.00     <#1>
     33.53    173.74      1.00     <#0>
     41.15    172.82      1.00     <#2>
     49.99    173.74      1.00     <#0>
     51.82    174.35      1.00     <#0>
     56.39    174.96      1.00     <#3>
     70.10    175.57      1.00     <#0>
     79.25    175.87      1.00     <#0>
*******************************
100
Mill Creek
           17074.000
COORDINATES
    0
FLOW DIRECTION
    0
DATUM
      0.00
RADIUS TYPE
    0
DIVIDE X-Section
0
SECTION ID

INTERPOLATED
    0
ANGLE
    0.00
PROFILE        8
      0.00    176.78      1.00     <#0>
     73.15    176.78      1.00     <#1>
     82.30    173.74      1.00     <#0>
```

```
     91.44    172.36      1.00     <#2>
     96.01    173.74      1.00     <#0>
    115.21    174.35      1.00     <#0>
    117.35    176.48      1.00     <#3>
    138.68    176.78      1.00     <#0>
*******************************
100
Mill Creek
           17276.000
COORDINATES
    0
FLOW DIRECTION
    0
DATUM
      0.00
RADIUS TYPE
    0
DIVIDE X-Section
0
SECTION ID

INTERPOLATED
    0
ANGLE
    0.00
PROFILE        18
      0.09    177.52      1.00     <#0>
     15.97    177.64      1.00     <#0>
     16.00    175.02      1.00     <#1>
     21.64    172.79      1.00     <#0>
     26.34    172.64      1.00     <#0>
     26.36    172.64      1.00     <#0>
     26.64    172.64      1.00     <#0>
     26.70    172.64      1.00     <#2>
     29.87    173.13      1.00     <#0>
     43.37    173.43      1.00     <#0>
     43.43    173.43      1.00     <#0>
     43.62    173.43      1.00     <#0>
     43.68    173.43      1.00     <#0>
     45.87    173.74      1.00     <#0>
     51.57    175.47      1.00     <#0>
     54.44    175.53      1.00     <#3>
     54.47    177.61      1.00     <#0>
     70.17    177.46      1.00     <#0>
*******************************
100
Mill Creek
           17514.000
COORDINATES
    0
FLOW DIRECTION
    0
```

```
DATUM
      0.00
RADIUS TYPE
    0
DIVIDE X-Section
0
SECTION ID

INTERPOLATED
    0
ANGLE
    0.00
PROFILE        13
    140.21    174.96      1.00     <#0>
    166.12    174.96      1.00     <#0>
    173.74    176.78      1.00     <#1>
    182.88    173.74      1.00     <#0>
    190.50    173.13      1.00     <#0>
    196.60    173.13      1.00     <#0>
    198.12    172.52      1.00     <#0>
    204.22    172.21      1.00     <#2>
    210.92    172.52      1.00     <#0>
    213.36    173.74      1.00     <#0>
    222.50    175.57      1.00     <#3>
    233.17    176.17      1.00     <#0>
    265.18    176.17      1.00     <#0>
*******************************
100
Mill Creek
           17971.000
COORDINATES
    0
FLOW DIRECTION
    0
DATUM
      0.00
RADIUS TYPE
    0
DIVIDE X-Section
0
SECTION ID

INTERPOLATED
    0
ANGLE
    0.00
PROFILE        12
    365.76    176.78      1.00     <#1>
    370.33    174.96      1.00     <#0>
    376.43    174.35      1.00     <#0>
    377.95    173.74      1.00     <#0>
    382.52    173.13      1.00     <#0>
```

388.62	172.52	1.00	<#0>
391.06	172.36	1.00	<#0>
404.47	171.72	1.00	<#2>
405.38	172.52	1.00	<#0>
411.48	173.74	1.00	<#0>
432.82	176.78	1.00	<#3>
509.02	176.78	1.00	<#0>

****

100

Mill Creek

18247.000

COORDINATES

0

FLOW DIRECTION

0

DATUM

0.00

RADIUS TYPE

0

DIVIDE X-Section

0

SECTION ID

INTERPOLATED

0

ANGLE

0.00

PROFILE 24

15.24	178.31	1.00	<#0>
18.29	176.08	1.00	<#0>
30.51	176.08	1.00	<#0>
47.06	174.44	1.00	<#0>
47.09	174.32	1.00	<#1>
48.98	174.19	1.00	<#0>
51.24	172.09	1.00	<#0>
52.70	171.42	1.00	<#2>
56.08	171.51	1.00	<#0>
59.01	172.30	1.00	<#0>
59.07	172.24	1.00	<#0>
60.35	172.30	1.00	<#0>
60.50	172.30	1.00	<#0>
64.89	171.66	1.00	<#0>
67.06	174.04	1.00	<#0>
69.95	174.16	1.00	<#0>
70.81	174.22	1.00	<#0>
71.29	174.22	1.00	<#0>
74.25	174.22	1.00	<#0>
74.26	174.26	1.00	<#3>
74.28	174.29	1.00	<#0>
74.31	174.35	1.00	<#0>
91.44	176.78	1.00	<#0>
94.49	178.31	1.00	<#0>

```
******************************
100
Mill Creek
           18674.000
COORDINATES
    0
FLOW DIRECTION
    0
DATUM
      0.00
RADIUS TYPE
    0
DIVIDE X-Section
0
SECTION ID

INTERPOLATED
    0
ANGLE
    0.00
PROFILE        11
    124.97    176.78      1.00     <#0>
    143.26    174.96      1.00     <#0>
    149.96    173.74      1.00     <#1>
    160.02    171.91      1.00     <#0>
    164.90    171.24      1.00     <#2>
    176.78    171.91      1.00     <#0>
    182.88    173.74      1.00     <#0>
    186.23    174.80      1.00     <#3>
    189.89    174.83      1.00     <#0>
    198.12    175.57      1.00     <#0>
    225.55    176.17      1.00     <#0>
******************************
100
Mill Creek
           18983.000
COORDINATES
    0
FLOW DIRECTION
    0
DATUM
      0.00
RADIUS TYPE
    0
DIVIDE X-Section
0
SECTION ID

INTERPOLATED
    0
ANGLE
    0.00
```

```
PROFILE        22
      0.00    175.50      1.00     <#0>
     31.21    175.84      1.00     <#0>
     31.27    174.32      1.00     <#1>
     40.63    173.19      1.00     <#0>
     43.56    172.00      1.00     <#0>
     43.59    172.00      1.00     <#0>
     43.80    171.88      1.00     <#0>
     43.89    171.94      1.00     <#0>
     45.81    171.63      1.00     <#0>
     50.48    171.30      1.00     <#0>
     53.46    171.18      1.00     <#2>
     59.38    171.76      1.00     <#0>
     59.47    171.69      1.00     <#0>
     59.68    171.69      1.00     <#0>
     59.71    171.69      1.00     <#0>
     61.57    171.60      1.00     <#0>
     66.05    173.43      1.00     <#0>
     71.78    174.44      1.00     <#3>
     71.81    175.96      1.00     <#0>
     87.63    175.99      1.00     <#0>
    137.16    174.96      1.00     <#0>
    198.12    174.96      1.00     <#0>
*******************************
100
Mill Creek
           19166.000
COORDINATES
    0
FLOW DIRECTION
    0
DATUM
      0.00
RADIUS TYPE
    0
DIVIDE X-Section
0
SECTION ID

INTERPOLATED
    0
ANGLE
    0.00
PROFILE        12
     77.72    176.78      1.00     <#0>
     85.34    174.35      1.00     <#0>
     98.15    173.74      1.00     <#0>
    106.07    173.13      1.00     <#1>
    111.56    171.30      1.00     <#0>
    115.82    170.87      1.00     <#2>
    119.79    171.30      1.00     <#0>
    123.44    173.13      1.00     <#3>
```

```
    124.36    173.74      1.00     <#0>
    144.78    174.35      1.00     <#0>
    213.36    174.35      1.00     <#0>
    219.46    176.78      1.00     <#0>
*******************************
100
Mill Creek
           19998.000
COORDINATES
    0
FLOW DIRECTION
    0
DATUM
      0.00
RADIUS TYPE
    0
DIVIDE X-Section
0
SECTION ID

INTERPOLATED
    0
ANGLE
    0.00
PROFILE        20
    128.02    173.04      1.00     <#0>
    128.32    172.79      1.00     <#0>
    128.63    172.49      1.00     <#0>
    148.38    172.36      1.00     <#0>
    155.48    172.24      1.00     <#0>
    162.12    171.88      1.00     <#1>
    162.31    171.88      1.00     <#0>
    169.62    169.87      1.00     <#0>
    171.85    169.65      1.00     <#0>
    173.74    169.56      1.00     <#0>
    175.35    169.44      1.00     <#0>
    176.11    169.01      1.00     <#0>
    176.39    169.01      1.00     <#2>
    178.92    169.71      1.00     <#0>
    178.95    170.90      1.00     <#0>
    178.95    171.39      1.00     <#3>
    193.97    173.92      1.00     <#0>
    195.35    174.32      1.00     <#0>
    199.92    174.32      1.00     <#0>
    204.06    173.10      1.00     <#0>
*******************************
100
Mill Creek
           20221.000
COORDINATES
    0
FLOW DIRECTION
```

```
    0
DATUM
      0.00
RADIUS TYPE
    0
DIVIDE X-Section
0
SECTION ID

INTERPOLATED
    0
ANGLE
    0.00
PROFILE        18
     24.38    173.13      1.00     <#0>
     54.86    173.13      1.00     <#0>
     59.44    174.35      1.00     <#0>
     70.10    174.35      1.00     <#0>
     76.20    173.74      1.00     <#0>
     79.25    173.13      1.00     <#1>
     82.30    172.52      1.00     <#0>
     83.21    171.91      1.00     <#0>
     85.34    170.69      1.00     <#0>
     85.95    170.38      1.00     <#0>
     87.17    169.62      1.00     <#0>
     91.44    169.38      1.00     <#2>
     96.01    169.62      1.00     <#0>
     99.06    170.69      1.00     <#0>
    103.63    171.45      1.00     <#0>
    107.90    172.21      1.00     <#0>
    109.73    172.52      1.00     <#3>
    152.40    172.82      1.00     <#0>
*******************************
100
Mill Creek
           20446.000
COORDINATES
    0
FLOW DIRECTION
    0
DATUM
      0.00
RADIUS TYPE
    0
DIVIDE X-Section
0
SECTION ID

INTERPOLATED
    0
ANGLE
    0.00
```

```
PROFILE        18
     23.96    175.02      1.00     <#0>
     43.46    172.91      1.00     <#1>
     43.49    172.91      1.00     <#0>
     53.95    171.48      1.00     <#0>
     54.10    171.48      1.00     <#0>
     55.35    171.48      1.00     <#0>
     55.44    171.42      1.00     <#0>
     58.61    171.39      1.00     <#0>
     60.99    169.68      1.00     <#0>
     66.39    169.04      1.00     <#2>
     66.54    169.10      1.00     <#0>
     67.91    169.16      1.00     <#0>
     68.00    169.16      1.00     <#0>
     70.29    169.71      1.00     <#0>
     73.06    172.43      1.00     <#0>
     76.90    173.52      1.00     <#0>
     76.93    173.52      1.00     <#3>
     95.71    175.44      1.00     <#0>
*******************************
100
Mill Creek
           20526.000
COORDINATES
    0
FLOW DIRECTION
    0
DATUM
      0.00
RADIUS TYPE
    0
DIVIDE X-Section
0
SECTION ID

INTERPOLATED
    0
ANGLE
    0.00
PROFILE        21
      0.00    175.17      1.00     <#0>
     11.25    175.17      1.00     <#0>
     22.07    173.46      1.00     <#0>
     30.30    172.88      1.00     <#1>
     30.72    172.85      1.00     <#0>
     38.37    172.49      1.00     <#0>
     40.20    170.78      1.00     <#0>
     42.03    171.05      1.00     <#0>
     44.62    169.53      1.00     <#0>
     45.54    168.80      1.00     <#0>
     47.21    168.71      1.00     <#2>
     50.26    169.01      1.00     <#0>
```

```
     52.09    169.56      1.00      <#0>
     55.14    170.63      1.00      <#0>
     56.81    171.60      1.00      <#0>
     59.41    172.18      1.00      <#0>
     65.50    172.70      1.00      <#0>
     65.62    172.43      1.00      <#3>
     76.17    172.85      1.00      <#0>
     81.96    175.17      1.00      <#0>
     97.35    175.20      1.00      <#0>
*******************************
100
Mill Creek
           20732.448
COORDINATES
    0
FLOW DIRECTION
    0
DATUM
      0.00
RADIUS TYPE
    0
DIVIDE X-Section
0
SECTION ID

INTERPOLATED
    1
ANGLE
    0.00
PROFILE        36
     98.90    174.11      1.00      <#0>
    108.95    173.91      1.00      <#0>
    118.61    173.27      1.00      <#0>
    121.19    173.16      1.00      <#0>
    122.14    172.92      1.00      <#0>
    122.78    172.68      1.00      <#0>
    123.42    172.22      1.00      <#0>
    124.37    171.97      1.00      <#0>
    125.01    171.73      1.00      <#0>
    125.96    171.26      1.00      <#1>
    126.39    171.10      1.00      <#0>
    126.58    171.03      1.00      <#0>
    127.49    170.79      1.00      <#0>
    128.41    170.56      1.00      <#0>
    129.02    170.44      1.00      <#0>
    133.99    170.07      1.00      <#0>
    135.80    169.51      1.00      <#0>
    137.62    169.47      1.00      <#0>
    138.19    169.35      1.00      <#0>
    140.20    168.98      1.00      <#0>
    141.10    168.76      1.00      <#0>
    142.77    168.68      1.00      <#2>
```

144.35	168.81	1.00	<#0>
145.30	168.98	1.00	<#0>
146.88	169.31	1.00	<#0>
147.32	169.45	1.00	<#0>
147.75	169.69	1.00	<#0>
149.10	170.17	1.00	<#0>
149.59	170.31	1.00	<#0>
152.26	171.20	1.00	<#0>
152.32	171.14	1.00	<#3>
154.43	171.84	1.00	<#0>
155.03	172.97	1.00	<#0>
163.24	173.05	1.00	<#0>
169.23	173.66	1.00	<#0>
185.15	173.67	1.00	<#0>

****

Appendix D: HEC RAS Cross-section Data

The HEC RAS cross-section data was imported from various HEC-2 text files and combined into one .G01 geometry file. The geometry file was the initial file used for the HEC RAS 3.0 flow model. For accurate depiction of the stream channel in the terrain model (as explained in the terrain model refinement process in Chapter 5), interpolated cross-sections were included to successive geometry files until an optimum number of cross-sections were attained. XY-coordinates were digitized from the modified terrain model and included in this file.

To better understand the data, the geometry file first provides the geometry file title and extent of the XY-coordinates used for the file. The second section describes the junctions and reaches within the geometry file. The rest of the geometry is broken down by reach, first defining the XY-coordinate points for each reach, then each cross-section within the reach.

Each cross-section in the file is defined by a River Station identification number and downstream reach lengths (for left overbank, stream centerline, and right overbank). The next section of data is the X- and Z- coordinates in space-delimited format (sequenced horizontally) defining the cross-section (unlike the columnar format for MIKE 11 cross-section files). The number of times Manning's n changes across the cross-section, and at what location follows the XZ-coordinate data. Lastly, left and right river bank coordinates, initial and incremental HTAB data (for unsteady flow calculations), whether the cross-section has been identified to provide a rating curve after processing (0 for no, 1 for yes), and expansion/contraction coefficients are shown.

HEC RAS 3.0 Geometry File from HEC-2 Data

```
Geom Title=pdc geometry from HEC02 cross-sections
Version=Version 3.0 Beta April 15, 2000
Viewing Rectangle= 432951.853815298, 433870.269332472 ,
146027.514925005, 140851.356231991

Junct Name=one
Junct Desc=, 0, 0, -1
Junct X Y & Text X
Y=433158.8981556,144927.5088831,433158.8981556,144927.5088831
Up River,Reach=PDC             ,Mill Creek
Up River,Reach=PDC             ,East Fork
Dn River,Reach=PDC             ,Mill Creek DS
Junc L&A=326,0
Junc L&A=0,0

River Reach=PDC             ,East Fork
Reach XY= 44
       433568.87       145914.24       433558.61       145864.87
       433551.56       145828.97        433541.3       145794.35
       433540.66       145750.76       433543.22       145702.68
       433550.27       145661.01       433549.63       145622.54
       433540.02        145564.2       433532.82        145530.7
       433531.19       145485.41       433529.24       145475.31
       433524.68       145465.21       433523.05       145445.34
       433518.81       145411.78       433511.32       145378.22
       433503.82       145347.59       433501.22       145326.09
       433495.68       145306.54       433487.86       145297.41
       433470.27       145288.94       433451.37       145281.12
       433389.46       145268.09       433346.13       145257.34
        433326.9       145248.54        433314.2       145236.49
       433304.42       145221.82       433301.49       145205.53
       433300.51       145184.68       433300.51       145151.45
       433298.56       145107.14       433297.25       145067.39
        433296.6       145049.79         433294.       145035.78
       433295.95       145018.19       433292.69        144995.7
       433284.55       144976.81        433275.1        144965.4
       433260.44       144967.36        433244.8       144971.27
       433223.94       144968.01       433198.86       144964.75
       433180.28       144957.91  433158.8981556  144927.5088831
Rch Text X Y=433466.3770389,145667.5572208
Reverse River Text= 0

Type RM Length L Ch R = 1 ,388     ,52.02,52.02,52.02
BEGIN DESCRIPTION:
5.1
 The East Fork Mill Creek HEC-2 model was developed by
 Water Resources & Coastal Engineering, Inc. under contract =
END DESCRIPTION:
Node Name=
#Sta/Elev= 18
```

```
20.12  179.22   43.28  178.61   60.35     178   60.96  177.91
66.17  175.14
71.66  175.14    72.3  175.63   74.92  177.24   79.25     178
79.55  181.05
129.54  181.05  135.03  178.31  164.59  177.09  178.31   177.7
178.61  178.31
179.83  181.05  217.02  178.31  262.74  178.31
#Mann= 4 ,-1 , 0
20.12     .06       0   60.96     .03       0   79.25    .045      0
79.55    .113       0
Bank Sta=60.35,79.25
XS Rating Curve= 0
XS HTab Starting El and Incr=175.438,.1
Exp/Cntr=.3,.1

Type RM Length L Ch R = 1 ,336     ,58,58,58
BEGIN DESCRIPTION:
199250
East Fork Mill Creek at Mill Creek station 199250
END DESCRIPTION:
Node Name=
#Sta/Elev= 24
0  182.88    3.14  182.27    4.48  181.66    6.34  181.05   12.89
179.83
16.28  179.22   20.12  178.61   26.27     178   43.04  177.39
57.79  177.39
57.79  177.36   58.64  176.78   60.81  174.96   65.87  174.96
68.37  176.17
69.98  176.78   71.38  177.42   74.46     178   78.67  177.39
84.77  176.78
180.78  177.39  197.24     178  217.81  178.61  234.45  178.61
#Mann= 3 , 0 , 0
0     .15       0   57.79  .05625       0   71.38     .15       0
Bank Sta=57.79,71.38
XS Rating Curve= 0
XS HTab Starting El and Incr=175.255,.1
Exp/Cntr=.3,.1

Type RM Length L Ch R = 1 ,278     ,56.96,56.96,56.96
BEGIN DESCRIPTION:
198820
East Fork Mill Creek at Mill Creek station 198820
END DESCRIPTION:
Node Name=
#Sta/Elev= 22
0  179.83     .18  179.22   24.87  178.61   27.95     178   29.08
177.39
30.45  176.78    31.3  176.17   32.77  175.57   37.92  174.44
39.53  175.57
41.15  176.17      42  176.78   44.32     178    44.5  178.03
47.27  178.61
51.66  178.61   55.02  177.39   65.01  176.78  132.47  176.78
```

```
218.05  176.78
249.75     178  263.29     178
#Mann= 3 , 0 , 0
0     .15       0   29.08  .05625       0   44.32     .15       0
Bank Sta=29.08,44.32
XS Rating Curve= 0
XS HTab Starting El and Incr=174.737,.1
Exp/Cntr=.3,.1

Type RM Length L Ch R = 1 ,221     ,119,119,119
BEGIN DESCRIPTION:
197690
East Fork Mill Creek at Mill Creek station 197690
END DESCRIPTION:
Node Name=
#Sta/Elev= 16
0  179.83     .12  178.61     .49     178   12.13  177.39   25.48
176.69
26.55  176.17   27.77  175.57   29.84  174.96   33.74  174.35
35.69  174.96
37.31  175.57   38.04  176.17   41.45  176.88   42.37  177.39
51.17  177.39
53.43  176.78
#Mann= 3 , 0 , 0
0     .15       0   25.48  .05625       0   38.04     .15       0
Bank Sta=25.48,38.04
XS Rating Curve= 0
XS HTab Starting El and Incr=174.646,.1
Exp/Cntr=.3,.1

Type RM Length L Ch R = 1 ,102     ,93.995,93.995,93.995
BEGIN DESCRIPTION:
196730
(Total flow reduced - Flow crosses from Mill Creek to East Fork Mill
=
Mill Creek confluence with East Fork Mill Creek at Mill Creek
station =
END DESCRIPTION:
Node Name=
#Sta/Elev= 10
0  176.78   54.86  176.78   59.44     178   61.57     178    70.1
174.35
71.63  173.13   73.15  173.13   77.72  174.35   91.44  175.87
182.88  175.87
#Mann= 3 , 0 , 0
0     .15       0    70.1  .05625       0   77.72     .15       0
Bank Sta=70.1,77.72
XS Rating Curve= 0
XS HTab Starting El and Incr=173.426,.1
Exp/Cntr=.3,.1

Type RM Length L Ch R = 1 ,8       ,8,8,8
```

```
BEGIN DESCRIPTION:
196000
Mill Creek total flow from CofE HEC-1 Model
Mill Creek (Main Stem)
END DESCRIPTION:
Node Name=
#Sta/Elev= 8
0  175.87   30.48  175.57   33.53  173.74   41.14 172.822   51.82
174.35
56.39  174.96    70.1  175.57   79.25  175.87
#Mann= 3 , 0 , 0
0     .15       0   30.48  .05625       0   56.39     .15       0
Bank Sta=30.48,56.39
XS Rating Curve= 0
XS HTab Starting El and Incr=173.122,.1
Exp/Cntr=.5,.3

Type RM Length L Ch R = 1 ,0       ,0,0,0
BEGIN DESCRIPTION:
196000
Mill Creek total flow from CofE HEC-1 Model
Mill Creek (Main Stem)
END DESCRIPTION:
Node Name=
#Sta/Elev= 8
0  175.87   30.48  175.57   33.53  173.74   41.15  172.82   51.82
174.35
56.39  174.96    70.1  175.57   79.25  175.87
#Mann= 3 , 0 , 0
0     .15       0   30.48  .05625       0   56.39     .15       0
Bank Sta=30.48,56.39
XS Rating Curve= 0
XS HTab Starting El and Incr=173.122,.1
Exp/Cntr=.5,.3

River Reach=PDC             ,Mill Creek
Reach XY= 26
       433142.53        145849.3       433134.11       145797.91
       433126.58       145728.37       433116.39       145689.39
       433073.42       145615.41       433054.82       145576.43
       433021.16       145533.02       433020.27       145507.77
        433024.7        145487.4        433037.1       145463.92
       433039.76       145451.96       433033.56       145409.44
       433041.09       145373.56       433045.52       145301.35
        433049.5       145284.52       433058.81       145270.79
       433064.12       145225.16       433064.12       145194.15
       433054.82       145173.78       433062.35       145152.96
       433065.01       145124.17       433067.67       145080.31
       433078.74       145044.88       433088.93       145003.24
       433126.14       144966.03  433158.8981556  144927.5088831
Rch Text X Y=433146.6220389,145618.8522208
Reverse River Text= 0
```

```
Type RM Length L Ch R = 1 ,45485   ,89.01,89.01,89.01
Node Name=
#Sta/Elev= 46
145.09   178.9  145.53  178.63  146.31  178.24  147.34  178.05
149.6  177.61
150.44   177.6  160.61  177.59  172.44  177.51  180.03  177.48
203.26  177.39
214.54  177.39  227.49  177.46  232.07  177.39  232.63   177.3
233.52  177.39
234.64  177.42  235.31  177.27     237  175.68  237.84  175.06
238.54  174.67
240.39  173.96   241.4  173.96  242.49   174.1  243.79  174.36
244.88  174.54
245.53  174.69  246.18  174.95  247.48  175.46  247.89  175.49
248.78  175.82
249.87  176.28  250.95  176.84  252.11  177.06  252.92  176.96
253.27  177.03
253.97  177.16  254.66  177.17  255.13  177.11  256.52   177.2
260.35   177.4
275.55  177.81  276.58  177.82  287.37  177.78  298.73  177.81
316.01  177.97
332.94  178.05
#Mann= 3 , 0 , 0
145.09     .15       0  235.31    .052       0  250.95     .15
0
Bank Sta=235.31,250.95
XS Rating Curve= 0
XS HTab Starting El and Incr=174.258,.1
Exp/Cntr=.3,.1

Type RM Length L Ch R = 1 ,45396   ,371,371,371
Node Name=
#Sta/Elev= 27
0  181.36     .31  178.16  167.55     178  190.44  177.85  198.12
177.36
198.36  177.36   200.5  176.78  202.48   176.3     204  174.65
205.07  174.47
206.9  174.01  206.93  174.01  207.39  173.95  207.51  173.95
210.28  173.92
212.57  174.53  213.06  175.05  216.53   175.2  218.97  175.78
219.09  175.78
219.58  175.84  219.61  175.84  224.61  176.66   228.6  177.55
228.72  177.55
426.72  178.13  427.03  181.36
#Mann= 3 , 0 , 0
0     .15       0  198.12  .05625       0   228.6     .15       0
Bank Sta=198.12,228.6
XS Rating Curve= 0
XS HTab Starting El and Incr=174.2189,.1
Exp/Cntr=.5,.3
```

```
Type RM Length L Ch R = 1 ,45025   ,341.38,344.42,344.42
Node Name=
#Sta/Elev= 12
0     178    3.05  176.78   30.48  176.48  109.73  176.78  194.46
176.78
196.6  176.17  198.12  174.96  201.17  173.74  202.69  173.74
210.31  176.78
323.09  176.78  329.18     178
#Mann= 3 , 0 , 0
0     .15       0   196.6  .05625       0  210.31     .15       0
Bank Sta=196.6,210.31
XS Rating Curve= 0
XS HTab Starting El and Incr=174.036,.1
Exp/Cntr=.3,.1

Type RM Length L Ch R = 1 ,44680   ,189,189,189
Node Name=
#Sta/Elev= 12
295.66  176.17  335.28  176.17  396.24  176.48   457.2  176.48
490.73  176.17
492.25  174.35  496.82  173.43  498.35  173.43  502.92  174.35
506.88  176.78
513.89  177.39  515.11     178
#Mann= 3 , 0 , 0
295.66     .15       0  490.73  .05625       0  506.88     .15     0
Bank Sta=490.73,506.88
XS Rating Curve= 0
XS HTab Starting El and Incr=173.7309,.1
Exp/Cntr=.3,.1

Type RM Length L Ch R = 1 ,44491   ,326,326,326
Node Name=
#Sta/Elev= 16
187.47  176.06  214.85  176.04     257   176.2  299.13  176.16
322.31  175.95
324.25  174.21  324.53   174.1  330.08  173.21  331.89   173.3
337.01  174.09
337.33  174.17  338.45  174.72  342.03  176.12  350.18  176.61
353.61   176.8
355.62  177.22
#Mann= 3 , 0 , 0
187.47     .15       0  322.31  .05625       0  342.03     .15
0
Bank Sta=322.31,342.03
XS Rating Curve= 0
XS HTab Starting El and Incr=173.508,.1
Exp/Cntr=.3,.1

River Reach=PDC             ,Mill Creek DS
Reach XY= 71
  433158.8981556  144927.5088831       433158.92       144927.49
       433177.52       144896.93       433175.31       144872.56
```

433220.05	144763.15	433234.22	144725.5
433250.17	144647.98	433259.91	144552.3
433263.01	144452.19	433276.75	144363.15
433269.21	144257.73	433278.07	144197.93
433266.11	144121.3	433254.15	144092.5
433255.48	144037.13	433254.6	143960.94
433239.09	143886.08	433244.85	143816.09
433239.98	143718.64	433235.55	143520.64
433220.49	143465.71	433228.46	143429.39
433247.07	143392.18	433252.38	143345.22
433252.38	143295.17	433252.38	143260.62
433262.57	143231.82	433267.89	143163.61
433264.34	143135.26	433269.21	143082.54
433276.75	143041.35	433285.16	142976.23
433282.06	142905.36	433274.97	142848.22
433278.07	142783.1	433283.83	142694.95
433278.52	142660.4	433275.86	142585.54
433279.4	142543.9	433267.44	142409.24
433245.74	142333.93	433235.55	142283.44
433237.76	142244.01	433235.99	142152.76
433244.41	142060.18	433243.52	141985.76
433260.36	141949.44	433280.29	141889.64
433312.18	141828.07	433339.65	141776.24
433418.05	141684.99	433445.51	141664.62
433508.86	141605.7	433523.03	141587.98
433558.91	141566.28	433614.28	141509.58
433643.52	141496.73	433668.33	141489.65
433697.12	141466.17	433726.8	141448.89
433760.46	141430.73	433813.62	141385.11
433830.01	141358.97	433837.1	141290.31
433833.11	141250.	433814.95	141194.63
433807.86	141116.67	433802.99	141041.37
433798.56	140958.09	433788.81	140928.85
433786.6	140903.6		

Rch Text X Y=433315.8236167,143921.5316623
Reverse River Text= 0

Type RM Length L Ch R = 1 ,44165   ,52,52,52
Node Name=
#Sta/Elev= 9
0 175.87   30.48 175.57   33.53 173.74   41.15 172.82   49.99
173.74
51.82 174.35   56.39 174.96   70.1 175.57   79.25 175.87
#Mann= 3 , 0 , 0
0   .15   0   30.48 .05625   0   56.39   .15   0
Bank Sta=30.48,56.39
XS Rating Curve= 0
XS HTab Starting El and Incr=173.1219,.1
Exp/Cntr=.5,.3

Type RM Length L Ch R = 1 ,44113   ,15.24,17.68,21.34
Node Name=

```
#Sta/Elev= 20
33.22  178.31    44.2  176.78   49.99  175.26   51.82  174.65
54.56  174.35
56.69  173.43    57.3  173.37   58.83  172.82   60.96  172.82
63.4  172.82
64.31  173.37   64.92  173.74   66.45  174.35   71.63  174.65
72.54  175.26
78.64  175.87   81.69  175.87   87.78  175.57  112.17  176.17
148.74  179.83
#Mann= 3 , 0 , 0
33.22     .15       0   49.99  .05625       0   72.54     .15       0
Bank Sta=49.99,72.54
XS Rating Curve= 0
XS HTab Starting El and Incr=173.1219,.1
Exp/Cntr=.3,.1

Type RM Length L Ch R = 1 ,44095   ,46,46,46
Node Name=
#Sta/Elev= 21
28.96  178.31   37.19  176.78   46.03  175.26   47.85  174.65
50.29  174.35
54.86  174.35   55.78  174.04   56.69  173.74   58.22  173.37
58.83  172.82
60.96  172.82   62.48  172.82    63.7  173.37   65.23  173.43
66.14  173.73
68.28  175.26   74.37  175.87   80.47  175.87  104.85  175.57
129.24  176.17
165.81  179.83
#Mann= 3 , 0 , 0
28.96     .15       0   46.03  .05625       0   68.28     .15       0
Bank Sta=46.03,68.28
XS Rating Curve= 0
XS HTab Starting El and Incr=173.1219,.1
Exp/Cntr=.5,.3

Type RM Length L Ch R = 1 ,44049   ,3,3,3
Node Name=
#Sta/Elev= 26
15.03   184.4   22.16  184.53   22.19  181.78   27.13  180.23
42.52  178.95
44.07  177.79   46.85  176.78   48.86  174.86   49.99  174.74
49.99   174.8
50.63  174.53   50.63  174.59   53.52  172.82   61.05  172.58
65.68  172.76
67.61   174.5    71.6  174.59   71.63  174.59   72.15  174.71
72.18  174.71
76.26  175.99   79.68  177.49    95.8  180.96  100.04  182.15
100.07  185.14
107.23   185.2
#Mann= 3 , 0 , 0
15.03     .15       0   22.19  .05625       0  100.04     .15       0
Bank Sta=22.19,100.04
```

```
XS Rating Curve= 0
XS HTab Starting El and Incr=172.8781,.1
Exp/Cntr=.5,.3

Type RM Length L Ch R = 1 ,44046   ,64,64,64
Node Name=
#Sta/Elev= 26
15.03   184.4   22.16  184.53   22.19  181.78   27.13  180.23
42.52  178.95
44.07  177.79   46.85  176.78   48.86  174.86   49.99  174.74
49.99   174.8
50.63  174.53   50.63  174.59   53.52  172.82   61.05  172.58
65.68  172.76
67.61  174.51    71.6  174.59   71.63  174.59   72.15  174.71
72.18  174.71
76.26  175.99   79.68  177.49    95.8  180.96  100.04  182.15
100.07  185.14
107.23   185.2
#Mann= 3 , 0 , 0
15.03     .15       0   22.19  .05625       0  100.04     .15
0
Bank Sta=22.19,100.04
XS Rating Curve= 0
XS HTab Starting El and Incr=172.8781,.1
Exp/Cntr=.5,.3

Type RM Length L Ch R = 1 ,43982   ,52,52,52
Node Name=
#Sta/Elev= 7
313.94  176.78  320.04  176.78  331.01  173.74  343.21  172.33
352.04  173.74
359.66  176.17  371.86  176.48
#Mann= 3 , 0 , 0
313.94     .15       0  320.04  .05625       0  359.66     .15     0
Bank Sta=320.04,359.66
XS Rating Curve= 0
XS HTab Starting El and Incr=172.6339,.1
Exp/Cntr=.5,.3

Type RM Length L Ch R = 1 ,43930   ,108.81,110.64,112.47
Node Name=
#Sta/Elev= 7
313.94  176.78  320.04  176.78  331.01  173.74  343.21  172.33
352.04  173.74
359.66  176.17  371.86  176.48
#Mann= 3 , 0 , 0
313.94     .15       0  320.04  .05625       0  359.66     .15     0
Bank Sta=320.04,359.66
XS Rating Curve= 0
XS HTab Starting El and Incr=172.6339,.1
Exp/Cntr=.3,.1
```

```
Type RM Length L Ch R = 1 ,43819   ,167.64,167.64,167.64
Node Name=
#Sta/Elev= 8
0  176.78   73.15  176.78    82.3  173.74   91.44  172.36   96.01
173.74
115.21  174.35  117.35  176.48  138.68  176.78
#Mann= 3 , 0 , 0
0     .15       0   73.15  .05625       0  117.35     .15       0
Bank Sta=73.15,117.35
XS Rating Curve= 0
XS HTab Starting El and Incr=172.6641,.1
Exp/Cntr=.3,.1

Type RM Length L Ch R = 1 ,43652   ,84,84,84
Node Name=
#Sta/Elev= 10
0  176.17   53.34  176.48   57.91  173.74   67.06  173.74   73.15
172.33
79.25  173.74   85.34  174.35   91.44  176.48  106.68  176.78
121.92  176.78
#Mann= 3 , 0 , 0
0     .15       0   53.34  .05625       0   91.44     .15       0
Bank Sta=53.34,91.44
XS Rating Curve= 0
XS HTab Starting El and Incr=172.6339,.1
Exp/Cntr=.5,.3

Type RM Length L Ch R = 1 ,43568   ,189,189,189
Node Name=
#Sta/Elev= 10
0  175.57   36.58  175.57    44.2  176.78   48.77  176.17   57.91
173.74
68.58  172.21   79.25  173.74      89  174.35   97.54  176.78
115.82  176.78
#Mann= 3 , 0 , 0
0     .15       0   48.77  .05625       0   97.54     .15       0
Bank Sta=48.77,97.54
XS Rating Curve= 0
XS HTab Starting El and Incr=172.512,.1
Exp/Cntr=.3,.1

Type RM Length L Ch R = 1 ,43379   ,706.95,706.95,706.95
Node Name=
#Sta/Elev= 13
140.21  174.96  166.12  174.96  173.74  176.78  182.88  173.74
190.5  173.13
196.6  173.13  198.12  172.52  204.22  172.21  210.92  172.52
213.36  173.74
222.5  175.57  233.17  176.17  265.18  176.17
#Mann= 3 , 0 , 0
140.21     .15       0  173.74   .0525       0   222.5     .15     0
Bank Sta=173.74,222.5
```

```
XS Rating Curve= 0
XS HTab Starting El and Incr=172.512,.1
Exp/Cntr=.3,.1

Type RM Length L Ch R = 1 ,42672   ,452.97,452.97,452.97
Node Name=
#Sta/Elev= 12
373.69  176.48  373.99  176.48  374.29  176.48   374.6  176.48
374.9  176.48
384.05  176.17  396.85  171.91  405.69  171.45  409.04   171.6
411.48  173.74
421.23  173.74  425.81  175.26
#Mann= 3 , 0 , 0
373.69     .15       0  384.05   .0525       0  411.48     .15     0
Bank Sta=384.05,411.48
XS Rating Curve= 0
XS HTab Starting El and Incr=171.75,.1
Exp/Cntr=.5,.3

Type RM Length L Ch R = 1 ,42219   ,265.18,263.96,262.13
Node Name=
#Sta/Elev= 11
124.97  176.78  143.26  174.96  149.96  173.74  160.02  171.91
164.9  171.24
176.78  171.91  182.88  173.74  186.23   174.8  189.89  174.83
198.12  175.57
225.55  176.17
#Mann= 3 , 0 , 0
124.97     .15       0  149.96   .0525       0  186.23     .15     0
Bank Sta=149.96,186.23
XS Rating Curve= 0
XS HTab Starting El and Incr=171.537,.1
Exp/Cntr=.3,.1

Type RM Length L Ch R = 1 ,41955   ,103,103,103
Node Name=
#Sta/Elev= 17
42.67  176.78   48.77  176.17   67.06  175.57   79.25  174.35
81.99  173.74
83.97  172.21   84.73  171.91   85.34   171.6   86.87   171.3
91.44  171.15
96.01   171.3   97.54   171.6   98.45  172.21  100.28  173.74
106.68  174.35
108.2  174.96  121.92  174.96
#Mann= 3 , 0 , 0
42.67     .15       0   81.99   .0525       0  100.28     .15      0
Bank Sta=81.99,100.28
XS Rating Curve= 0
XS HTab Starting El and Incr=171.4449,.1
Exp/Cntr=.5,.3

Type RM Length L Ch R = 1 ,41852   ,121.92,125.28,126.48
```

```
Node Name=
#Sta/Elev= 15
91.44  175.57   94.49  174.96   99.06  174.36  100.89  173.74
102.72  172.21
104.24  171.51  112.78  170.99  115.82  170.99  118.26  170.99
122.23  171.51
124.97  173.13   126.8  173.74  131.06  175.57   152.4  175.87
167.64  175.87
#Mann= 3 , 0 , 0
91.44     .15       0   99.06  .05625       0  124.97     .15      0
Bank Sta=99.06,124.97
XS Rating Curve= 0
XS HTab Starting El and Incr=171.2931,.1
Exp/Cntr=.3,.1

Type RM Length L Ch R = 1 ,41727   ,152.4,152.4,152.4
Node Name=
#Sta/Elev= 12
77.72  176.78   85.34  174.35   98.15  173.74  106.07  173.13
111.56   171.3
115.82  170.87  119.79   171.3  123.44  173.13  124.36  173.74
144.78  174.35
213.36  174.35  219.46  176.78
#Mann= 3 , 0 , 0
77.72     .15       0  106.07  .05625       0  123.44     .15      0
Bank Sta=106.07,123.44
XS Rating Curve= 0
XS HTab Starting El and Incr=171.1709,.1
Exp/Cntr=.3,.1

Type RM Length L Ch R = 1 ,41574   ,106,106,106
Node Name=
#Sta/Elev= 19
60.96  176.17    76.2  174.96   80.16  173.74   82.91  172.52
83.82  172.21
85.04  171.91   86.87   171.3   87.78  171.08      89  170.69
91.44   170.6
93.88  170.69    95.1  171.08   95.71   171.6   97.23  172.21
108.2  172.52
126.5  173.13  129.54  173.74  134.11  174.96   146.3  175.57
#Mann= 3 , 0 , 0
60.96     .15       0   83.82  .05625       0   97.23     .15      0
Bank Sta=83.82,97.23
XS Rating Curve= 0
XS HTab Starting El and Incr=170.8969,.1
Exp/Cntr=.5,.3

Type RM Length L Ch R = 1 ,41468   ,393.21,393.21,393.21
Node Name=
#Sta/Elev= 19
60.96  176.17    76.2  174.96   80.16  173.74   82.91  172.52
83.82  172.21
```

```
85.04  171.91   86.87   171.3   87.78  171.08      89  170.69
91.44   170.6
93.88  170.69    95.1  171.08   95.71   171.6   97.23  172.21
108.2  172.52
126.49  173.13  129.54  173.74  134.11  174.96   146.3  175.57
#Mann= 3 , 0 , 0
60.96     .15       0   83.82  .05625       0   97.23     .15      0
Bank Sta=83.82,97.23
XS Rating Curve= 0
XS HTab Starting El and Incr=170.8969,.1
Exp/Cntr=.3,.1

Type RM Length L Ch R = 1 ,41074   ,179.83,179.83,179.83
Node Name=
#Sta/Elev= 18
0  173.43     .03  173.43   45.72  173.43    82.3  173.13   84.13
172.52
85.65  172.21   87.78  170.69   88.39  170.57   89.31  170.08
91.44  169.84
93.27  170.08   94.49  170.57   96.93  170.69   99.06  171.91
100.58  172.52
155.45     173  182.88  173.13   228.6  173.13
#Mann= 3 , 0 , 0
0     .15       0   84.13  .05625       0   99.06     .15       0
Bank Sta=84.13,99.06
XS Rating Curve= 0
XS HTab Starting El and Incr=170.1349,.1
Exp/Cntr=.3,.1

Type RM Length L Ch R = 1 ,40895   ,223.41,223.41,223.41
Node Name=
#Sta/Elev= 20
128.02  173.04  128.32  172.79  128.63  172.49  148.38  172.36
155.48  172.24
162.12  171.88  162.31  171.88  169.62  169.87  171.85  169.65
173.74  169.45
175.35  169.44  176.11  169.01  176.39  169.01  178.92  169.71
178.95   170.9
178.95  171.39  193.98  173.92  195.35  174.32  199.92  174.32
204.06   173.1
#Mann= 3 , 0 , 0
128.02     .15       0  162.12  .05625       0  178.95     .15     0
Bank Sta=162.12,178.95
XS Rating Curve= 0
XS HTab Starting El and Incr=169.3119,.1
Exp/Cntr=.5,.3

Type RM Length L Ch R = 1 ,40672   ,187.44,186.54,185.94
Node Name=
#Sta/Elev= 18
24.38  173.13   54.86  173.13   59.44  174.35    70.1  174.35
76.2  173.74
```

```
79.25  173.13    82.3  172.52   83.21  171.91   85.34  170.69
85.95  170.38
87.17  169.62   91.44  169.38   96.01  169.62   99.06  170.69
103.63  171.45
107.9  172.21  109.73  172.52   152.4  172.82
#Mann= 3 , 0 , 0
24.38     .15       0   79.25  .05625       0  109.73     .15      0
Bank Sta=79.25,109.73
XS Rating Curve= 0
XS HTab Starting El and Incr=169.677,.1
Exp/Cntr=.3,.1

Type RM Length L Ch R = 1 ,40486   ,67,67,67
Node Name=
#Sta/Elev= 20
51.82  172.52   64.01  172.52    70.1  173.13   74.37  174.35
77.72  174.35
78.64  174.04   79.86  173.74   82.91  172.21   85.04  170.69
85.65  170.08
86.87  169.47   91.44  169.16   96.01  169.47   97.54  170.08
98.45  170.69
102.72  172.21  104.85  172.82  106.07  173.13  115.82  173.74
137.16  173.74
#Mann= 3 , 0 , 0
51.82     .15       0   82.91  .05625       0  102.72     .15      0
Bank Sta=82.91,102.72
XS Rating Curve= 0
XS HTab Starting El and Incr=169.464,.1
Exp/Cntr=.7,.5

Type RM Length L Ch R = 1 ,40419   ,3.35,3.35,3.35
Node Name=
#Sta/Elev= 21
52.43  176.78   52.73  175.26   67.67  174.96   71.02  174.04
71.93  173.74
75.9  172.52   82.91   171.3   85.65  170.69   86.56  170.08   87.48
169.16
91.44  169.16   94.49  169.16   96.01  170.08   96.62  170.38   7.23
170.69
100.28  170.99  103.94   171.3   108.2   171.6  109.73  172.21
112.78  173.74
113.08  176.78
#Mann= 3 , 0 , 0
52.43     .15       0   82.91  .05625       0  100.28     .15
0
Bank Sta=82.91,100.28
XS Rating Curve= 0
XS HTab Starting El and Incr=169.464,.1
Exp/Cntr=.7,.5

Type RM Length L Ch R = 1 ,40415   ,29,29,29
Node Name=
```

```
#Sta/Elev= 21
52.43  176.78   52.73  175.26   67.67  174.96   71.02  174.04
71.93  173.74
75.9  172.52   82.91   171.3   85.65  170.69   86.56  170.08   87.48
169.16
91.44  169.16   94.49  169.16   96.01  170.08   96.62  170.38
97.23  170.69
100.28  170.99  103.94   171.3   108.2   171.6  109.73  172.21
112.78  173.74
113.08  176.78
#Mann= 3 , 0 , 0
52.43     .15       0   82.91  .05625       0  100.28     .15      0
Bank Sta=82.91,100.28
XS Rating Curve= 0
XS HTab Starting El and Incr=169.464,.1
Exp/Cntr=.7,.5

Type RM Length L Ch R = 1 ,40386   ,6,6,6
Node Name=
#Sta/Elev= 25
24.9  177.64   42.92  177.85   42.98  172.52   46.09  171.88   48.25
171.48
50.9  171.12   53.71  170.72    53.8  170.66   55.57  170.38   55.57
170.32
57.85  169.07   58.74  169.07   61.14  169.07   63.55  169.07
65.23  169.07
66.6   170.2   66.66  170.26   68.28   170.6   68.34  170.66   71.48
171.05
73.88   171.3   76.26  171.63   79.34  171.91   79.37   178.1
95.1  178.28
#Mann= 3 , 0 , 0
24.9     .15       0   42.98  .05625       0   79.34     .15       0
Bank Sta=42.98,79.34
XS Rating Curve= 0
XS HTab Starting El and Incr=169.3729,.1
Exp/Cntr=.7,.5

Type RM Length L Ch R = 1 ,40380   ,98,98,98
Node Name=
#Sta/Elev= 25
24.9  177.64   42.92  177.85   42.98  172.52   46.09  171.88   48.25
171.48
50.9  171.12   53.71  170.72    53.8  170.66   55.57  170.38   55.57
170.32
57.85  168.86   58.74  168.92   61.14  168.95   63.55  168.92
65.23  168.92
66.6   170.2   66.66  170.26   68.28   170.6   68.34  170.66   71.48
171.05
73.88   171.3   76.26  171.63   79.34  171.91   79.37   178.1
95.1  178.28
#Mann= 3 , 0 , 0
24.9     .15       0   42.98  .05625       0   79.34     .15       0
```

```
Bank Sta=42.98,79.34
XS Rating Curve= 0
XS HTab Starting El and Incr=169.1589,.1
Exp/Cntr=.7,.5

Type RM Length L Ch R = 1 ,40282   ,121.5,121.5,121.5
Node Name=
#Sta/Elev= 17
70.1  172.52   82.91  171.91   84.73  171.91   85.95     171   86.87
170.69
87.78  169.71   90.83  169.16   92.96  169.16   96.01  169.16
98.15  169.71
100.58  170.69  102.41   171.3  106.68  172.21  117.04  172.52
149.35  172.52
155.45  173.74  161.54  174.96
#Mann= 3 , 0 , 0
70.1     .15       0   84.73  .05625       0  102.41     .15       0
Bank Sta=84.73,102.41
XS Rating Curve= 0
XS HTab Starting El and Incr=169.464,.1
Exp/Cntr=.5,.3

Type RM Length L Ch R = 1 ,40160.5 ,105.92,102.49,100.58
Node Name=
#Sta/Elev= 31
102.11  173.13   118.8  172.53  119.52  172.37  119.84  172.26
119.99  172.21
120.47  171.91  121.19  171.76  121.66   171.6  122.38   171.3
122.79  171.06
123.42  170.79  124.04  170.51  124.46  170.35  124.66  170.29
126.38  170.04
128.09  169.45  130.69  169.16  133.81  168.92  134.87  168.92
136.4  168.92
138.53  169.26  139.45  169.47  140.97  170.15   142.8  170.99
145.76  171.86
146.13  172.24  146.61  172.68  154.22  172.82  179.46  172.82
184.22  173.43
188.98  174.04
#Mann= 3 , 0 , 0
102.11     .15       0  122.38    .056       0   142.8     .15     0
Bank Sta=122.38,142.8
XS Rating Curve= 0
XS HTab Starting El and Incr=169.22,.1
Exp/Cntr=.5,.3
```

Appendix E: HEC HMS Input for MIKE 11

The hydrograph data used for both the HEC HMS and MIKE 11 models is the same. The data is displayed in two sections. The first section shown is the upstream (for East Fork and Mill Creek) and downstream (for Mill Creek) boundary data in 4-minute time steps. The upstream data is flow hydrographs and the downstream data is stage hydrographs. The second section is flow data derived from the HEC HMS model. It was inputted into both models at 15-minute time steps. The flow data was extracted from the hydrologic model from the DSS utility for the HEC RAS model. For both sections, corresponding HEC RAS River Stations and MIKE 11 Chainages are provided for each boundary input.

Table E-1. Mill Creek PDC model's upstream and downstream boundary data.

Time Step #:	**Date:**	**Time:**	**h (meters):**	**U/S Mill Creek Q (m^3/s)**	**U/S East Fork Q (m^3/s)**
		Chainage:	***20732.45***	***15407.15***	***11427.12***
		River Station:	***18.83***	***5179.47***	***1173.84***
1	4/15/1998	12:00	169.324	1.300	1.132
2	4/15/1998	12:04	169.324	1.300	1.134
3	4/15/1998	12:08	169.324	1.300	1.151
4	4/15/1998	12:12	169.324	1.300	1.138
5	4/15/1998	12:16	169.324	1.300	1.129
6	4/15/1998	12:20	169.324	1.300	1.130
7	4/15/1998	12:24	169.324	1.300	1.130
8	4/15/1998	12:28	169.324	1.300	1.133
9	4/15/1998	12:32	169.324	1.300	1.136
10	4/15/1998	12:36	169.324	1.300	1.139
11	4/15/1998	12:40	169.324	1.300	1.141
12	4/15/1998	12:44	169.324	1.300	1.141
13	4/15/1998	12:48	169.324	1.300	1.141
14	4/15/1998	12:52	169.324	1.300	1.141
15	4/15/1998	12:56	169.324	1.300	1.140
16	4/15/1998	13:00	169.324	1.300	1.139
17	4/15/1998	13:04	169.324	1.300	1.138

Time Step #:	Date:	Time:	h (meters):	U/S Mill Creek Q (m^3/s)	U/S East Fork Q (m^3/s)
		Chainage:	***20732.45***	***15407.15***	***11427.12***
		River Station:	***18.83***	***5179.47***	***1173.84***
18	4/15/1998	13:08	169.324	1.300	1.137
19	4/15/1998	13:12	169.324	1.300	1.137
20	4/15/1998	13:16	169.324	1.300	1.136
21	4/15/1998	13:20	169.324	1.300	1.135
22	4/15/1998	13:24	169.324	1.300	1.135
23	4/15/1998	13:28	169.324	1.300	1.134
24	4/15/1998	13:32	169.324	1.300	1.134
25	4/15/1998	13:36	169.324	1.300	1.134
26	4/15/1998	13:40	169.324	1.300	1.134
27	4/15/1998	13:44	169.324	1.300	1.133
28	4/15/1998	13:48	169.324	1.300	1.133
29	4/15/1998	13:52	169.324	1.300	1.133
30	4/15/1998	13:56	169.324	1.300	1.133
31	4/15/1998	14:00	169.324	1.300	1.133
32	4/15/1998	14:04	169.324	1.300	1.133
33	4/15/1998	14:08	169.324	1.300	1.133
34	4/15/1998	14:12	169.324	1.300	1.133
35	4/15/1998	14:16	169.324	1.300	1.133
36	4/15/1998	14:20	169.324	1.300	1.133
37	4/15/1998	14:24	169.324	1.300	1.133
38	4/15/1998	14:28	169.324	1.300	1.133
39	4/15/1998	14:32	169.324	1.300	1.133
40	4/15/1998	14:36	169.324	1.300	1.133
41	4/15/1998	14:40	169.324	1.300	1.133
42	4/15/1998	14:44	169.324	1.300	1.133
43	4/15/1998	14:48	169.324	1.300	1.133
44	4/15/1998	14:52	169.324	1.300	1.133
45	4/15/1998	14:56	169.324	1.300	1.133
46	4/15/1998	15:00	169.324	1.300	1.133
47	4/15/1998	15:04	169.324	1.300	1.133
48	4/15/1998	15:08	169.324	1.300	1.133
49	4/15/1998	15:12	169.324	1.300	1.133
50	4/15/1998	15:16	169.324	1.300	1.133
51	4/15/1998	15:20	169.324	1.300	1.133
52	4/15/1998	15:24	169.324	1.300	1.133
53	4/15/1998	15:28	169.324	1.300	1.133

Time Step #:	Date:	Time:	h (meters):	U/S Mill Creek Q (m^3/s)	U/S East Fork Q (m^3/s)
		Chainage:	***20732.45***	***15407.15***	***11427.12***
		River Station:	***18.83***	***5179.47***	***1173.84***
54	4/15/1998	15:32	169.324	1.300	1.133
55	4/15/1998	15:36	169.324	1.300	1.133
56	4/15/1998	15:40	169.324	1.300	1.133
57	4/15/1998	15:44	169.324	1.300	1.133
58	4/15/1998	15:48	169.324	1.300	1.133
59	4/15/1998	15:52	169.324	1.300	1.133
60	4/15/1998	15:56	169.324	1.300	1.133
61	4/15/1998	16:00	169.324	1.300	1.133
62	4/15/1998	16:04	169.324	1.300	1.133
63	4/15/1998	16:08	169.324	1.300	1.133
64	4/15/1998	16:12	169.324	1.300	1.133
65	4/15/1998	16:16	169.324	1.300	1.133
66	4/15/1998	16:20	169.324	1.300	1.133
67	4/15/1998	16:24	169.324	1.300	1.133
68	4/15/1998	16:28	169.324	1.300	1.133
69	4/15/1998	16:32	169.324	1.300	1.133
70	4/15/1998	16:36	169.324	1.300	1.133
71	4/15/1998	16:40	169.324	1.300	1.133
72	4/15/1998	16:44	169.324	1.300	1.133
73	4/15/1998	16:48	169.324	1.300	1.133
74	4/15/1998	16:52	169.324	1.300	1.133
75	4/15/1998	16:56	169.324	1.300	1.133
76	4/15/1998	17:00	169.324	1.300	1.133
77	4/15/1998	17:04	169.324	1.300	1.133
78	4/15/1998	17:08	169.324	1.300	1.133
79	4/15/1998	17:12	169.324	1.300	1.133
80	4/15/1998	17:16	169.324	1.300	1.133
81	4/15/1998	17:20	169.324	1.300	1.133
82	4/15/1998	17:24	169.324	1.300	1.133
83	4/15/1998	17:28	169.324	1.300	1.133
84	4/15/1998	17:32	169.324	1.300	1.133
85	4/15/1998	17:36	169.324	1.300	1.133
86	4/15/1998	17:40	169.324	1.300	1.133
87	4/15/1998	17:44	169.324	1.300	1.133
88	4/15/1998	17:48	169.324	1.300	1.133
89	4/15/1998	17:52	169.324	1.300	1.133

Time Step #:	Date:	Time:	h (meters):	U/S Mill Creek Q (m^3/s)	U/S East Fork Q (m^3/s)
		Chainage:	***20732.45***	***15407.15***	***11427.12***
		River Station:	***18.83***	***5179.47***	***1173.84***
90	4/15/1998	17:56	169.324	1.300	1.133
91	4/15/1998	18:00	169.324	1.300	1.133
92	4/15/1998	18:04	169.324	1.300	1.133
93	4/15/1998	18:08	169.324	1.300	1.133
94	4/15/1998	18:12	169.324	1.300	1.133
95	4/15/1998	18:16	169.324	1.300	1.133
96	4/15/1998	18:20	169.324	1.300	1.133
97	4/15/1998	18:24	169.324	1.300	1.133
98	4/15/1998	18:28	169.324	1.300	1.133
99	4/15/1998	18:32	169.324	1.300	1.133
100	4/15/1998	18:36	169.324	1.300	1.133
101	4/15/1998	18:40	169.324	1.300	1.133
102	4/15/1998	18:44	169.324	1.300	1.133
103	4/15/1998	18:48	169.324	1.300	1.133
104	4/15/1998	18:52	169.324	1.300	1.133
105	4/15/1998	18:56	169.324	1.300	1.133
106	4/15/1998	19:00	169.324	1.300	1.133
107	4/15/1998	19:04	169.324	1.300	1.133
108	4/15/1998	19:08	169.324	1.300	1.133
109	4/15/1998	19:12	169.324	1.300	1.133
110	4/15/1998	19:16	169.324	1.300	1.133
111	4/15/1998	19:20	169.324	1.300	1.133
112	4/15/1998	19:24	169.324	1.300	1.133
113	4/15/1998	19:28	169.324	1.300	1.133
114	4/15/1998	19:32	169.324	1.300	1.133
115	4/15/1998	19:36	169.324	1.300	1.133
116	4/15/1998	19:40	169.324	1.300	1.133
117	4/15/1998	19:44	169.324	1.300	1.133
118	4/15/1998	19:48	169.324	1.300	1.133
119	4/15/1998	19:52	169.324	1.300	1.133
120	4/15/1998	19:56	169.324	1.300	1.133
121	4/15/1998	20:00	169.324	1.300	1.133
122	4/15/1998	20:04	169.324	1.300	1.133
123	4/15/1998	20:08	169.324	1.300	1.133
124	4/15/1998	20:12	169.324	1.300	1.133
125	4/15/1998	20:16	169.324	1.300	1.133

Time Step #:	Date:	Time:	h (meters):	U/S Mill Creek Q (m^3/s)	U/S East Fork Q (m^3/s)
		Chainage:	***20732.45***	***15407.15***	***11427.12***
		River Station:	***18.83***	***5179.47***	***1173.84***
126	4/15/1998	20:20	169.324	1.300	1.133
127	4/15/1998	20:24	169.324	1.300	1.133
128	4/15/1998	20:28	169.324	1.300	1.133
129	4/15/1998	20:32	169.324	1.300	1.133
130	4/15/1998	20:36	169.324	1.300	1.133
131	4/15/1998	20:40	169.324	1.300	1.133
132	4/15/1998	20:44	169.324	1.300	1.133
133	4/15/1998	20:48	169.324	1.300	1.133
134	4/15/1998	20:52	169.324	1.300	1.133
135	4/15/1998	20:56	169.324	1.300	1.133
136	4/15/1998	21:00	169.324	1.300	1.133
137	4/15/1998	21:04	169.324	1.300	1.133
138	4/15/1998	21:08	169.324	1.300	1.133
139	4/15/1998	21:12	169.324	1.300	1.133
140	4/15/1998	21:16	169.324	1.300	1.133
141	4/15/1998	21:20	169.324	1.300	1.133
142	4/15/1998	21:24	169.324	1.300	1.133
143	4/15/1998	21:28	169.324	1.300	1.133
144	4/15/1998	21:32	169.324	1.300	1.133
145	4/15/1998	21:36	169.324	1.300	1.133
146	4/15/1998	21:40	169.324	1.300	1.133
147	4/15/1998	21:44	169.324	1.300	1.133
148	4/15/1998	21:48	169.324	1.300	1.133
149	4/15/1998	21:52	169.324	1.300	1.133
150	4/15/1998	21:56	169.324	1.300	1.133
151	4/15/1998	22:00	169.324	1.300	1.133
152	4/15/1998	22:04	169.324	1.300	1.133
153	4/15/1998	22:08	169.324	1.300	1.133
154	4/15/1998	22:12	169.324	1.300	1.133
155	4/15/1998	22:16	169.324	1.300	1.133
156	4/15/1998	22:20	169.324	1.300	1.133
157	4/15/1998	22:24	169.324	1.300	1.133
158	4/15/1998	22:28	169.324	1.300	1.133
159	4/15/1998	22:32	169.324	1.300	1.133
160	4/15/1998	22:36	169.324	1.300	1.133
161	4/15/1998	22:40	169.324	1.300	1.133

Time Step #:	Date:	Time:	h (meters):	U/S Mill Creek Q (m^3/s)	U/S East Fork Q (m^3/s)
		Chainage:	***20732.45***	***15407.15***	***11427.12***
		River Station:	***18.83***	***5179.47***	***1173.84***
162	4/15/1998	22:44	169.324	1.300	1.133
163	4/15/1998	22:48	169.324	1.300	1.133
164	4/15/1998	22:52	169.324	1.300	1.133
165	4/15/1998	22:56	169.324	1.300	1.133
166	4/15/1998	23:00	169.324	1.300	1.133
167	4/15/1998	23:04	169.324	1.300	1.133
168	4/15/1998	23:08	169.324	1.300	1.133
169	4/15/1998	23:12	169.324	1.300	1.133
170	4/15/1998	23:16	169.324	1.300	1.133
171	4/15/1998	23:20	169.324	1.300	1.133
172	4/15/1998	23:24	169.324	1.300	1.133
173	4/15/1998	23:28	169.324	1.300	1.133
174	4/15/1998	23:32	169.324	1.300	1.133
175	4/15/1998	23:36	169.324	1.300	1.133
176	4/15/1998	23:40	169.324	1.300	1.133
177	4/15/1998	23:44	169.324	1.300	1.133
178	4/15/1998	23:48	169.324	1.300	1.133
179	4/15/1998	23:52	169.324	1.300	1.133
180	4/15/1998	23:56	169.324	1.300	1.133
181	4/15/1998	0:00	169.324	1.300	1.133
182	4/16/1998	0:04	169.324	1.300	1.133
183	4/16/1998	0:08	169.324	1.300	1.133
184	4/16/1998	0:12	169.324	1.300	1.133
185	4/16/1998	0:16	169.324	1.300	1.133
186	4/16/1998	0:20	169.324	1.300	1.133
187	4/16/1998	0:24	169.324	1.300	1.133
188	4/16/1998	0:28	169.324	1.300	1.133
189	4/16/1998	0:32	169.324	1.300	1.133
190	4/16/1998	0:36	169.324	1.300	1.133
191	4/16/1998	0:40	169.324	1.300	1.133
192	4/16/1998	0:44	169.324	1.300	1.133
193	4/16/1998	0:48	169.324	1.300	1.133
194	4/16/1998	0:52	169.324	1.300	1.133
195	4/16/1998	0:56	169.324	1.300	1.133
196	4/16/1998	1:00	169.324	1.300	1.133
197	4/16/1998	1:04	169.324	1.300	1.133

Time Step #:	Date:	Time:	h (meters):	U/S Mill Creek Q (m^3/s)	U/S East Fork Q (m^3/s)
		Chainage:	***20732.45***	***15407.15***	***11427.12***
		River Station:	***18.83***	***5179.47***	***1173.84***
198	4/16/1998	1:08	169.324	1.300	1.133
199	4/16/1998	1:12	169.324	1.300	1.133
200	4/16/1998	1:16	169.324	1.300	1.133
201	4/16/1998	1:20	169.324	1.300	1.133
202	4/16/1998	1:24	169.324	1.300	1.133
203	4/16/1998	1:28	169.324	1.300	1.133
204	4/16/1998	1:32	169.324	1.300	1.133
205	4/16/1998	1:36	169.324	1.300	1.133
206	4/16/1998	1:40	169.324	1.300	1.133
207	4/16/1998	1:44	169.324	1.300	1.133
208	4/16/1998	1:48	169.324	1.300	1.133
209	4/16/1998	1:52	169.324	1.300	1.133
210	4/16/1998	1:56	169.324	1.300	1.133
211	4/16/1998	2:00	169.324	1.300	1.133
212	4/16/1998	2:04	169.324	1.300	1.133
213	4/16/1998	2:08	169.324	1.300	1.133
214	4/16/1998	2:12	169.324	1.300	1.133
215	4/16/1998	2:16	169.324	1.300	1.133
216	4/16/1998	2:20	169.324	1.300	1.133
217	4/16/1998	2:24	169.324	1.300	1.133
218	4/16/1998	2:28	169.324	1.300	1.133
219	4/16/1998	2:32	169.324	1.300	1.133
220	4/16/1998	2:36	169.324	1.300	1.133
221	4/16/1998	2:40	169.324	1.300	1.133
222	4/16/1998	2:44	169.324	1.300	1.133
223	4/16/1998	2:48	169.324	1.300	1.133
224	4/16/1998	2:52	169.324	1.300	1.133
225	4/16/1998	2:56	169.324	1.299	1.133
226	4/16/1998	3:00	169.325	1.298	1.133
227	4/16/1998	3:04	169.325	1.297	1.133
228	4/16/1998	3:08	169.327	1.295	1.133
229	4/16/1998	3:12	169.329	1.290	1.133
230	4/16/1998	3:16	169.333	1.286	1.133
231	4/16/1998	3:20	169.338	1.281	1.133
232	4/16/1998	3:24	169.345	1.274	1.133
233	4/16/1998	3:28	169.354	1.265	1.133

Time Step #:	Date:	Time:	h (meters):	U/S Mill Creek Q (m^3/s)	U/S East Fork Q (m^3/s)
		Chainage:	***20732.45***	***15407.15***	***11427.12***
		River Station:	***18.83***	***5179.47***	***1173.84***
234	4/16/1998	3:32	169.367	1.255	1.133
235	4/16/1998	3:36	169.382	1.242	1.134
236	4/16/1998	3:40	169.400	1.227	1.136
237	4/16/1998	3:44	169.422	1.209	1.140
238	4/16/1998	3:48	169.447	1.189	1.148
239	4/16/1998	3:52	169.476	1.164	1.161
240	4/16/1998	3:56	169.508	1.132	1.183
241	4/16/1998	4:00	169.542	1.095	1.218
242	4/16/1998	4:04	169.579	1.056	1.272
243	4/16/1998	4:08	169.620	1.002	1.352
244	4/16/1998	4:12	169.663	0.929	1.470
245	4/16/1998	4:16	169.709	0.853	1.651
246	4/16/1998	4:20	169.757	0.779	1.908
247	4/16/1998	4:24	169.808	0.679	2.305
248	4/16/1998	4:28	169.861	0.560	2.894
249	4/16/1998	4:32	169.916	0.461	3.710
250	4/16/1998	4:36	169.973	0.377	4.840
251	4/16/1998	4:40	170.033	0.246	6.210
252	4/16/1998	4:44	170.095	0.161	7.768
253	4/16/1998	4:48	170.159	0.225	9.982
254	4/16/1998	4:52	170.226	0.353	12.192
255	4/16/1998	4:56	170.295	0.578	14.890
256	4/16/1998	5:00	170.365	1.014	17.828
257	4/16/1998	5:04	170.437	1.709	20.904
258	4/16/1998	5:08	170.511	2.612	24.273
259	4/16/1998	5:12	170.585	3.691	27.221
260	4/16/1998	5:16	170.661	5.012	30.811
261	4/16/1998	5:20	170.738	6.489	33.738
262	4/16/1998	5:24	170.815	8.177	37.233
263	4/16/1998	5:28	170.893	10.155	40.111
264	4/16/1998	5:32	170.973	11.986	42.969
265	4/16/1998	5:36	171.057	14.594	45.745
266	4/16/1998	5:40	171.147	17.775	47.707
267	4/16/1998	5:44	171.250	21.117	49.903
268	4/16/1998	5:48	171.364	24.638	51.111
269	4/16/1998	5:52	171.493	27.686	52.540

Time Step #:	Date:	Time:	h (meters):	U/S Mill Creek Q (m^3/s)	U/S East Fork Q (m^3/s)
		Chainage:	***20732.45***	***15407.15***	***11427.12***
		River Station:	***18.83***	***5179.47***	***1173.84***
270	4/16/1998	5:56	171.637	31.025	53.072
271	4/16/1998	6:00	171.791	33.802	53.334
272	4/16/1998	6:04	171.950	36.910	53.347
273	4/16/1998	6:08	172.108	41.461	52.995
274	4/16/1998	6:12	172.267	44.970	52.414
275	4/16/1998	6:16	172.429	47.884	51.316
276	4/16/1998	6:20	172.595	51.821	50.346
277	4/16/1998	6:24	172.745	54.563	48.899
278	4/16/1998	6:28	172.889	57.644	47.583
279	4/16/1998	6:32	173.024	60.604	45.792
280	4/16/1998	6:36	173.148	63.031	44.325
281	4/16/1998	6:40	173.264	65.900	42.364
282	4/16/1998	6:44	173.369	68.001	40.765
283	4/16/1998	6:48	173.466	70.496	38.754
284	4/16/1998	6:52	173.553	72.566	37.065
285	4/16/1998	6:56	173.633	74.582	35.143
286	4/16/1998	7:00	173.705	76.627	33.482
287	4/16/1998	7:04	173.772	78.181	31.693
288	4/16/1998	7:08	173.829	80.194	30.011
289	4/16/1998	7:12	173.883	81.522	28.445
290	4/16/1998	7:16	173.930	83.178	26.884
291	4/16/1998	7:20	173.973	84.381	25.532
292	4/16/1998	7:24	174.010	85.809	24.072
293	4/16/1998	7:28	174.045	86.910	22.942
294	4/16/1998	7:32	174.074	87.960	21.693
295	4/16/1998	7:36	174.101	89.047	20.758
296	4/16/1998	7:40	174.123	89.893	19.689
297	4/16/1998	7:44	174.143	90.892	18.965
298	4/16/1998	7:48	174.161	91.425	18.147
299	4/16/1998	7:52	174.176	92.429	17.582
300	4/16/1998	7:56	174.189	92.847	16.992
301	4/16/1998	8:00	174.200	93.591	16.578
302	4/16/1998	8:04	174.210	93.989	16.208
303	4/16/1998	8:08	174.217	94.514	15.903
304	4/16/1998	8:12	174.225	95.050	15.690
305	4/16/1998	8:16	174.229	95.135	15.474

Time Step #:	Date:	Time:	h (meters):	U/S Mill Creek Q (m^3/s)	U/S East Fork Q (m^3/s)
		Chainage:	***20732.45***	***15407.15***	***11427.12***
		River Station:	***18.83***	***5179.47***	***1173.84***
306	4/16/1998	8:20	174.234	95.813	15.361
307	4/16/1998	8:24	174.236	95.720	15.209
308	4/16/1998	8:28	174.238	96.356	15.147
309	4/16/1998	8:32	174.238	96.181	15.037
310	4/16/1998	8:36	174.238	96.580	14.973
311	4/16/1998	8:40	174.235	96.651	14.897
312	4/16/1998	8:44	174.233	96.625	14.811
313	4/16/1998	8:48	174.229	96.942	14.739
314	4/16/1998	8:52	174.224	96.594	14.615
315	4/16/1998	8:56	174.218	97.069	14.526
316	4/16/1998	9:00	174.210	96.579	14.345
317	4/16/1998	9:04	174.202	96.902	14.177
318	4/16/1998	9:08	174.192	96.621	13.939
319	4/16/1998	9:12	174.182	96.573	13.699
320	4/16/1998	9:16	174.170	96.604	13.390
321	4/16/1998	9:20	174.158	96.115	13.062
322	4/16/1998	9:24	174.143	96.446	12.690
323	4/16/1998	9:28	174.129	95.694	12.323
324	4/16/1998	9:32	174.112	96.011	11.904
325	4/16/1998	9:36	174.096	95.302	11.516
326	4/16/1998	9:40	174.077	95.321	11.068
327	4/16/1998	9:44	174.058	94.901	10.685
328	4/16/1998	9:48	174.037	94.427	10.227
329	4/16/1998	9:52	174.016	94.376	9.864
330	4/16/1998	9:56	173.993	93.481	9.409
331	4/16/1998	10:00	173.969	93.570	9.070
332	4/16/1998	10:04	173.945	92.560	8.627
333	4/16/1998	10:08	173.919	92.437	8.309
334	4/16/1998	10:12	173.894	91.674	7.887
335	4/16/1998	10:16	173.866	91.051	7.581
336	4/16/1998	10:20	173.839	90.714	7.198
337	4/16/1998	10:24	173.810	89.548	6.899
338	4/16/1998	10:28	173.781	89.526	6.569
339	4/16/1998	10:32	173.751	88.107	6.279
340	4/16/1998	10:36	173.720	88.011	6.009
341	4/16/1998	10:40	173.689	86.754	5.735

Time Step #:	Date:	Time:	h (meters):	U/S Mill Creek Q (m^3/s)	U/S East Fork Q (m^3/s)
		Chainage:	***20732.45***	***15407.15***	***11427.12***
		River Station:	***18.83***	***5179.47***	***1173.84***
342	4/16/1998	10:44	173.658	86.187	5.509
343	4/16/1998	10:48	173.626	85.443	5.261
344	4/16/1998	10:52	173.594	84.233	5.068
345	4/16/1998	10:56	173.561	83.943	4.854
346	4/16/1998	11:00	173.528	82.383	4.671
347	4/16/1998	11:04	173.495	82.132	4.500
348	4/16/1998	11:08	173.462	80.749	4.336
349	4/16/1998	11:12	173.429	79.977	4.199
350	4/16/1998	11:16	173.395	79.228	4.041
351	4/16/1998	11:20	173.362	77.719	3.920
352	4/16/1998	11:24	173.328	77.537	3.785
353	4/16/1998	11:28	173.294	75.628	3.673
354	4/16/1998	11:32	173.260	75.498	3.553
355	4/16/1998	11:36	173.227	73.879	3.454
356	4/16/1998	11:40	173.193	73.130	3.348
357	4/16/1998	11:44	173.159	72.263	3.248
358	4/16/1998	11:48	173.125	70.720	3.157
359	4/16/1998	11:52	173.092	70.461	3.063
360	4/16/1998	11:56	173.058	68.612	2.983
361	4/16/1998	12:00	173.024	68.249	2.892
362	4/16/1998	12:04	172.990	66.911	2.818
363	4/16/1998	12:08	172.956	65.769	2.754
364	4/16/1998	12:12	172.923	65.308	2.670
365	4/16/1998	12:16	172.889	63.400	2.618
366	4/16/1998	12:20	172.855	63.402	2.560
367	4/16/1998	12:24	172.821	61.484	2.492
368	4/16/1998	12:28	172.788	61.065	2.434
369	4/16/1998	12:32	172.754	59.941	2.383
370	4/16/1998	12:36	172.721	58.651	2.320
371	4/16/1998	12:40	172.688	58.350	2.280
372	4/16/1998	12:44	172.654	56.575	2.216
373	4/16/1998	12:48	172.621	56.293	2.172
374	4/16/1998	12:52	172.588	54.978	2.133
375	4/16/1998	12:56	172.555	53.936	2.091
376	4/16/1998	13:00	172.522	53.494	2.055
377	4/16/1998	13:04	172.489	51.801	2.019

Time Step #:	Date:	Time:	h (meters):	U/S Mill Creek Q (m^3/s)	U/S East Fork Q (m^3/s)
		Chainage:	***20732.45***	***15407.15***	***11427.12***
		River Station:	***18.83***	***5179.47***	***1173.84***
378	4/16/1998	13:08	172.456	51.787	1.989
379	4/16/1998	13:12	172.423	50.227	1.950
380	4/16/1998	13:16	172.390	49.672	1.924
381	4/16/1998	13:20	172.358	48.832	1.891
382	4/16/1998	13:24	172.325	47.624	1.862
383	4/16/1998	13:28	172.293	47.222	1.838
384	4/16/1998	13:32	172.261	45.923	1.811
385	4/16/1998	13:36	172.231	45.335	1.780
386	4/16/1998	13:40	172.201	44.592	1.753
387	4/16/1998	13:44	172.170	43.640	1.718
388	4/16/1998	13:48	172.139	43.199	1.686
389	4/16/1998	13:52	172.108	41.986	1.651
390	4/16/1998	13:56	172.078	41.672	1.622
391	4/16/1998	14:00	172.047	40.849	1.593
392	4/16/1998	14:04	172.017	40.150	1.570
393	4/16/1998	14:08	171.987	39.469	1.546
394	4/16/1998	14:12	171.957	38.713	1.520
395	4/16/1998	14:16	171.927	38.051	1.506
396	4/16/1998	14:20	171.898	37.102	1.483
397	4/16/1998	14:24	171.869	36.466	1.471
398	4/16/1998	14:28	171.841	35.915	1.452
399	4/16/1998	14:32	171.813	35.029	1.439
400	4/16/1998	14:36	171.785	34.593	1.421
401	4/16/1998	14:40	171.757	33.777	1.403
402	4/16/1998	14:44	171.729	33.271	1.387
403	4/16/1998	14:48	171.701	32.586	1.372
404	4/16/1998	14:52	171.673	31.964	1.356
405	4/16/1998	14:56	171.645	31.370	1.343
406	4/16/1998	15:00	171.618	30.771	1.328
407	4/16/1998	15:04	171.591	30.164	1.318
408	4/16/1998	15:08	171.564	29.627	1.305
409	4/16/1998	15:12	171.538	29.009	1.296
410	4/16/1998	15:16	171.512	28.568	1.285
411	4/16/1998	15:20	171.486	27.955	1.278
412	4/16/1998	15:24	171.460	27.535	1.266
413	4/16/1998	15:28	171.434	26.964	1.259

Time Step #:	Date:	Time:	h (meters):	U/S Mill Creek Q (m^3/s)	U/S East Fork Q (m^3/s)
		Chainage:	***20732.45***	***15407.15***	***11427.12***
		River Station:	***18.83***	***5179.47***	***1173.84***
414	4/16/1998	15:32	171.409	26.533	1.248
415	4/16/1998	15:36	171.384	26.007	1.242
416	4/16/1998	15:40	171.359	25.566	1.231
417	4/16/1998	15:44	171.334	25.066	1.227
418	4/16/1998	15:48	171.310	24.642	1.218
419	4/16/1998	15:52	171.286	24.153	1.214
420	4/16/1998	15:56	171.263	23.775	1.206
421	4/16/1998	16:00	171.239	23.278	1.203
422	4/16/1998	16:04	171.216	22.910	1.196
423	4/16/1998	16:08	171.193	22.437	1.193
424	4/16/1998	16:12	171.170	22.065	1.187
425	4/16/1998	16:16	171.148	21.612	1.184
426	4/16/1998	16:20	171.126	21.246	1.179
427	4/16/1998	16:24	171.104	20.804	1.176
428	4/16/1998	16:28	171.082	20.447	1.172
429	4/16/1998	16:32	171.061	20.021	1.170
430	4/16/1998	16:36	171.039	19.706	1.166
431	4/16/1998	16:40	171.019	19.307	1.164
432	4/16/1998	16:44	170.998	18.988	1.160
433	4/16/1998	16:48	170.978	18.608	1.159
434	4/16/1998	16:52	170.958	18.313	1.155
435	4/16/1998	16:56	170.938	17.953	1.155
436	4/16/1998	17:00	170.919	17.660	1.151
437	4/16/1998	17:04	170.899	17.308	1.151
438	4/16/1998	17:08	170.880	17.019	1.148
439	4/16/1998	17:12	170.861	16.677	1.148
440	4/16/1998	17:16	170.842	16.398	1.145
441	4/16/1998	17:20	170.824	16.047	1.146
442	4/16/1998	17:24	170.805	15.767	1.143
443	4/16/1998	17:28	170.787	15.427	1.143
444	4/16/1998	17:32	170.770	15.156	1.141
445	4/16/1998	17:36	170.753	14.839	1.142
446	4/16/1998	17:40	170.736	14.577	1.142
447	4/16/1998	17:44	170.719	14.272	1.145
448	4/16/1998	17:48	170.703	14.031	1.149
449	4/16/1998	17:52	170.688	13.740	1.158

Time Step #:	Date:	Time:	h (meters):	U/S Mill Creek Q (m^3/s)	U/S East Fork Q (m^3/s)
		Chainage:	***20732.45***	***15407.15***	***11427.12***
		River Station:	***18.83***	***5179.47***	***1173.84***
450	4/16/1998	17:56	170.672	13.498	1.171
451	4/16/1998	18:00	170.657	13.214	1.193
452	4/16/1998	18:04	170.643	12.986	1.225
453	4/16/1998	18:08	170.628	12.714	1.270
454	4/16/1998	18:12	170.614	12.487	1.332
455	4/16/1998	18:16	170.601	12.226	1.414
456	4/16/1998	18:20	170.587	12.011	1.522
457	4/16/1998	18:24	170.575	11.763	1.654
458	4/16/1998	18:28	170.563	11.563	1.810
459	4/16/1998	18:32	170.551	11.333	1.987
460	4/16/1998	18:36	170.539	11.151	2.186
461	4/16/1998	18:40	170.528	10.941	2.394
462	4/16/1998	18:44	170.517	10.780	2.596
463	4/16/1998	18:48	170.506	10.596	2.789
464	4/16/1998	18:52	170.496	10.459	2.962
465	4/16/1998	18:56	170.485	10.298	3.122
466	4/16/1998	19:00	170.475	10.180	3.245

Table E-2. Mill Creek PDC model's lateral boundary data extracted from the HEC HMS model.

Time Step #:	Date:	Time:	Basin 109 Runoff (m^3/s)	Basin 110 Runoff (m^3/s)	Basin 111 Runoff (m^3/s)	Basin 115 Runoff (m^3/s)	Basins 112 - 117 Runoff (m^3/s)
		Chainage:	***15829.00***	***16443.00***	***15850.00***	***20000.00***	***20248.00***
		River Station:	***4822.09***	***4043.30***	***4577.87***	***525.69***	***336.56***
1	4/15/1998	12:00	0	0	0	0	0
2	4/15/1998	12:15	0	0	0	0	0
3	4/15/1998	12:30	0	0	0	0	0
4	4/15/1998	12:45	0	0	0	0	0
5	4/15/1998	13:00	0	0	0	0	0
6	4/15/1998	13:15	0	0	0	0	0
7	4/15/1998	13:30	0	0	0	0	0
8	4/15/1998	13:45	0	0	0	0	0
9	4/15/1998	14:00	0	0	0	0	0
10	4/15/1998	14:15	0	0	0	0	0
11	4/15/1998	14:30	0	0	0	0	0
12	4/15/1998	14:45	0	0	0	0	0
13	4/15/1998	15:00	0	0	0	0	0
14	4/15/1998	15:15	0	0	0	0	0
15	4/15/1998	15:30	0	0	0	0	0
16	4/15/1998	15:45	0	0	0	0	0
17	4/15/1998	16:00	0	0	0	0	0
18	4/15/1998	16:15	0	0	0	0	0
19	4/15/1998	16:30	0	0	0	0	0
20	4/15/1998	16:45	0	0	0	0	0
21	4/15/1998	17:00	0	0	0	0	0
22	4/15/1998	17:15	0	0	0	0	0
23	4/15/1998	17:30	0	0	0	0	0
24	4/15/1998	17:45	0	0	0	0	0
25	4/15/1998	18:00	0	0	0	0	0
26	4/15/1998	18:15	0	0	0	0	0
27	4/15/1998	18:30	0	0	0	0	0
28	4/15/1998	18:45	0	0	0	0	0
29	4/15/1998	19:00	0	0	0	0	0
30	4/15/1998	19:15	0	0	0	0	0
31	4/15/1998	19:30	0	0	0	0	0
32	4/15/1998	19:45	0	0	0	0	0

Time Step #:	Date:	Time:	Basin 109 Runoff (m^3/s)	Basin 110 Runoff (m^3/s)	Basin 111 Runoff (m^3/s)	Basin 115 Runoff (m^3/s)	Basins 112 - 117 Runoff (m^3/s)
		Chainage:	***15829.00***	***16443.00***	***15850.00***	***20000.00***	***20248.00***
		River Station:	***4822.09***	***4043.30***	***4577.87***	***525.69***	***336.56***
33	4/15/1998	20:00	0	0	0	0	0
34	4/15/1998	20:15	0	0	0	0	0
35	4/15/1998	20:30	0	0	0	0	0
36	4/15/1998	20:45	0	0	0	0	0
37	4/15/1998	21:00	0	0	0	0	0
38	4/15/1998	21:15	0	0	0	0	0
39	4/15/1998	21:30	0	0	0	0	0
40	4/15/1998	21:45	0	0	0	0	0
41	4/15/1998	22:00	0	0	0	0	0
42	4/15/1998	22:15	0	0	0	0	0
43	4/15/1998	22:30	0	0	0	0	0
44	4/15/1998	22:45	0	0	0	0	0
45	4/15/1998	23:00	0	0	0	0	0
46	4/15/1998	23:15	0	0	0	0	0
47	4/15/1998	23:30	0	0	0	0	0
48	4/15/1998	23:45	0	0	0	0	0
49	4/15/1998	0:00	0	0	0	0	0
50	4/16/1998	0:15	0	0	0	0	0
51	4/16/1998	0:30	0	0	0	0	0
52	4/16/1998	0:45	0	0	0	0	0
53	4/16/1998	1:00	0	0	0	0	0
54	4/16/1998	1:15	0	0	0	0	0
55	4/16/1998	1:30	0	0	0	0	0
56	4/16/1998	1:45	0	0	0	0	0
57	4/16/1998	2:00	0	0	0	0	0
58	4/16/1998	2:15	0	0	0	0	0
59	4/16/1998	2:30	0	0	0	0	0
60	4/16/1998	2:45	0	0	0	0	0
61	4/16/1998	3:00	0.03	0.006	0.032	0.043	0.034
62	4/16/1998	3:15	0.151	0.0316	0.155	0.198	0.25
63	4/16/1998	3:30	0.367	0.0783	0.382	0.465	0.832
64	4/16/1998	3:45	0.694	0.1482	0.732	0.865	1.846
65	4/16/1998	4:00	1.163	0.248	1.237	1.424	3.248
66	4/16/1998	4:15	1.88	0.4042	2.004	2.26	5.032

Time Step #:	Date:	Time:	Basin 109 Runoff (m^3/s)	Basin 110 Runoff (m^3/s)	Basin 111 Runoff (m^3/s)	Basin 115 Runoff (m^3/s)	Basins 112 - 117 Runoff (m^3/s)
		Chainage:	***15829.00***	***16443.00***	***15850.00***	***20000.00***	***20248.00***
		River Station:	***4822.09***	***4043.30***	***4577.87***	***525.69***	***336.56***
67	4/16/1998	4:30	2.9	0.6269	3.091	3.453	7.317
68	4/16/1998	4:45	4.37	0.9416	4.589	5.163	10.239
69	4/16/1998	5:00	6.248	1.3418	6.449	7.391	13.92
70	4/16/1998	5:15	8.485	1.812	8.595	10.084	18.174
71	4/16/1998	5:30	10.984	2.3372	10.976	13.142	22.548
72	4/16/1998	5:45	13.776	2.909	13.54	16.558	26.537
73	4/16/1998	6:00	16.746	3.5188	16.189	20.224	29.838
74	4/16/1998	6:15	19.86	4.1353	18.784	24.149	32.293
75	4/16/1998	6:30	22.88	4.7278	21.208	28.096	33.86
76	4/16/1998	6:45	25.693	5.2432	23.245	31.896	34.615
77	4/16/1998	7:00	28.098	5.6607	24.779	35.318	34.561
78	4/16/1998	7:15	29.968	5.9592	25.834	38.187	33.764
79	4/16/1998	7:30	31.318	6.1468	26.414	40.381	32.46
80	4/16/1998	7:45	32.135	6.2362	26.565	41.911	30.866
81	4/16/1998	8:00	32.505	6.2279	26.291	42.877	29.163
82	4/16/1998	8:15	32.448	6.1302	25.691	43.274	27.557
83	4/16/1998	8:30	31.977	5.9602	24.789	43.092	26.067
84	4/16/1998	8:45	31.155	5.7344	23.759	42.467	24.64
85	4/16/1998	9:00	30.085	5.4774	22.604	41.389	23.242
86	4/16/1998	9:15	28.844	5.1956	21.33	39.998	21.839
87	4/16/1998	9:30	27.45	4.8787	19.933	38.416	20.427
88	4/16/1998	9:45	25.916	4.539	18.517	36.657	19.023
89	4/16/1998	10:00	24.225	4.1923	17.124	34.633	17.675
90	4/16/1998	10:15	22.478	3.861	15.797	32.447	16.399
91	4/16/1998	10:30	20.728	3.5481	14.563	30.124	15.192
92	4/16/1998	10:45	19.112	3.2603	13.392	27.839	14.065
93	4/16/1998	11:00	17.599	2.9925	12.275	25.662	13.022
94	4/16/1998	11:15	16.182	2.7401	11.225	23.646	12.05
95	4/16/1998	11:30	14.855	2.504	10.246	21.762	11.16
96	4/16/1998	11:45	13.629	2.2872	9.302	19.981	10.352
97	4/16/1998	12:00	12.474	2.0807	8.387	18.331	9.611
98	4/16/1998	12:15	11.405	1.8806	7.52	16.789	8.942
99	4/16/1998	12:30	10.38	1.6903	6.708	15.345	8.335
100	4/16/1998	12:45	9.386	1.5138	5.962	13.98	7.788

Time Step #:	Date:	Time:	Basin 109 Runoff (m^3/s)	Basin 110 Runoff (m^3/s)	Basin 111 Runoff (m^3/s)	Basin 115 Runoff (m^3/s)	Basins 112 - 117 Runoff (m^3/s)
		Chainage:	***15829.00***	***16443.00***	***15850.00***	***20000.00***	***20248.00***
		River Station:	***4822.09***	***4043.30***	***4577.87***	***525.69***	***336.56***
101	4/16/1998	13:00	8.459	1.3503	5.287	12.668	7.297
102	4/16/1998	13:15	7.602	1.2038	4.676	11.425	6.862
103	4/16/1998	13:30	6.803	1.0705	4.129	10.276	6.48
104	4/16/1998	13:45	6.09	0.949	3.657	9.214	6.141
105	4/16/1998	14:00	5.444	0.8443	3.244	8.26	5.838
106	4/16/1998	14:15	4.864	0.7531	2.878	7.413	5.567
107	4/16/1998	14:30	4.36	0.6704	2.555	6.646	5.323
108	4/16/1998	14:45	3.914	0.598	2.269	5.976	5.102
109	4/16/1998	15:00	3.506	0.5333	2.018	5.382	4.9
110	4/16/1998	15:15	3.145	0.4756	1.792	4.837	4.715
111	4/16/1998	15:30	2.824	0.4247	1.591	4.351	4.545
112	4/16/1998	15:45	2.532	0.3787	1.413	3.919	4.39
113	4/16/1998	16:00	2.273	0.3379	1.253	3.524	4.245
114	4/16/1998	16:15	2.042	0.3011	1.112	3.169	4.111
115	4/16/1998	16:30	1.831	0.2681	0.988	2.853	3.984
116	4/16/1998	16:45	1.642	0.2395	0.877	2.568	3.865
117	4/16/1998	17:00	1.474	0.2136	0.779	2.308	3.752
118	4/16/1998	17:15	1.322	0.1902	0.697	2.077	3.644
119	4/16/1998	17:30	1.187	0.1699	0.627	1.883	3.543
120	4/16/1998	17:45	1.082	0.1551	0.584	1.727	3.477
121	4/16/1998	18:00	1.001	0.1449	0.561	1.608	3.476
122	4/16/1998	18:15	0.943	0.1393	0.557	1.522	3.545
123	4/16/1998	18:30	0.908	0.137	0.573	1.462	3.663
124	4/16/1998	18:45	0.891	0.1388	0.616	1.431	3.784
125	4/16/1998	19:00	0.891	0.1442	0.682	1.436	3.881

Appendix F: Data Dictionary

Data	Description	Class	Attribute	Units
3dxsectsef	Shape file of East Fork cross-sections for use in terrain model modification	PolylineZ	XYZ coordinates	Meters
3dxsectsmc	Shape file of Mill Creek cross-sections for use in terrain model modification	PolylineZ	XYZ coordinates	Meters
Bnd1	MIKE 11 boundary file depicting base flow conditions of study area	.BND11	Time-series boundary conditions	m^3/s, Meters
Bnd1PDC1	MIKE 11 boundary file depicting flow conditions of study area’s 25-yr storm event	.BND11	Time-series boundary conditions	m^3/s, Meters
Channelbds	Shape file created from stream channel bounds for modifying terrain model	Polygon	XYZ coordinates	Meters
Crtin1	TIN of initial terrain model, without stream features	TIN	Elevation	Meters
Eastpdcreachpts	Shape file of East Fork points extracted from *Nwtin1*, used to defined stream network	Point	XY coordinate	Meters

Data	Description	Class	Attribute	Units
Efclip	Shape file of clipped East Fork cross-sections of the stream channel	PolylineZ	XYZ coordinates	Meters
Floodmap	GIS project file for - terrain model modification	.apr		
Gridpts	Shape file of point elevations created from the *Pdcgrid1* file, for integrating stream features into terrain model	Point	Elevation	Meters
HDPar1	MIKE 11 hydrodynamic parameter file of study area	.HD11	Manning's *n* values	
Hpoints.txt	Shape file of MIKE 11 simulation results	Point	Time-series stage height	Meters
Mcclip	Shape file of clipped Mill Creek cross-sections of the stream channel	PolylineZ	XYZ coordinates	Meters
Millpdcreachpts	Shape file of Mill Creek points extracted from *Nwtin1*, used to defined stream network	Point	XY coordinate	Meters
MllCreek_CSO	DSS file created from HEC HMS model	.dss	Runoff hydrographs	m^3/s
Nwtin1	TIN of modified terrain model, with stream features	TIN	Elevation	Meters

Data	Description	Class	Attribute	Units
Pdc1	MIKE 11 simulation data created from flow model	.MSD	Time-series data	m^3/s, Meters
Pdc1	MIKE 11 simulation file for study area’s 25-yr storm event	.SIM11		
pdc1hotstart	MIKE 11 simulation file establishing the study area’s initial conditions	.SIM11		
pdc1model	MIKE 11 network file of study area	.NWK11	XY coordinates, Chainage	Meters
pdc2ftcontrs	Shape file with 2-ft contour lines for the PDC study area	Polyline	Elevation	Meters
pdc5	RAS geometry file of study area	.g01		
pdc5	RAS GIS export file exported from RAS model into GIS	.gis	Time-series stage heights	Meters
pdc5	RAS plan file of study area	.p01		
pdc5	RAS project file of study area	.prj		
pdc5	RAS unsteady flow file of study area	.u01		
Pdcbanks	Shape file of GeoRAS stream banks	Polyline	XY coordinates	Meters
Pdcdem	Grid of modified terrain model, with stream features	5-m Grid	Elevation	Meters

Data	Description	Class	Attribute	Units
Pdcflowpath	Shape file of GeoRAS stream and overbank flow paths	Polyline	XY coordinates, River Stationing	Meters
Pdcgrid1	Grid of initial terrain model, without stream features	5-m Grid	Elevation	Meters
pdcinput1	GIS import file created by GeoRAS for HEC RAS	.geo	XYZ coordinates	Meters
PDCstream1	Shape file of GeoRAS stream centerline	Polyline	XY coordinates	Meters
PDCstream3D1	Shape file of GeoRAS stream centerline	PolylineZ	XYZ coordinates	Meters
pdctmpts	Shape file of point elevations created from 30-m DEM, for developing initial terrain model	Point	Elevation	Meters
pdcXSec1	MIKE 11 cross-section file of study area using HEC-2 data	.XNS11	XZ coordinates	Meters
Qpoints.txt	Shape file of MIKE 11 simulation results	Point	Time-series flow	m^3/s
rd3clip	Shape file of study area road network	Polyline	XY coordinates	Meters
Stream1	Shape file of study area's stream network, digitized from stream points	Polyline	XY coordinates	Meters

Data	Description	Class	Attribute	Units
Stream3def1	Shape file of East Fork stream and channel banks	PolylineZ	XYZ coordinates	Meters
Stream3dmc1	Shape file of Mill Creek stream and channel banks	PolylineZ	XYZ coordinates	Meters
theme1	Shape file used as boundary for study area	Polygon	XY coordinates	Meters
TS1EastUSQ	MIKE 11 time-series file of East Fork upstream base flow	.dfs0	Time-series flow	m^3/s
TS1MillDShlevel	MIKE 11 time-series file of Mill Creek downstream base stage	.dfs0	Time-series stage height	Meters
TS1MillUSQ	MIKE 11 time-series file of Mill Creek upstream base flow	.dfs0	Time-series flow	m^3/s
TS2Basin109Q	MIKE 11 time-series file of Basin 109 runoff for 25-yr storm	.dfs0	Time-series flow	m^3/s
TS2Basin110Q	MIKE 11 time-series file of Basin 110 runoff for 25-yr storm	.dfs0	Time-series flow	m^3/s
TS2Basin111Q	MIKE 11 time-series file of Basin 111 runoff for 25-yr storm	.dfs0	Time-series flow	m^3/s

Data	Description	Class	Attribute	Units
TS2Basin112_117Q	MIKE 11 time-series file of Basins 112 thru 117 (minus 115) for 25-yr storm	.dfs0	Time-series flow	m^3/s
TS2Basin115Q	MIKE 11 time-series file of Basin 115 runoff for 25-yr storm	.dfs0	Time-series flow	m^3/s
TS2EastUSQ	MIKE 11 time-series file of East Fork upstream flow for 25-yr storm	.dfs0	Time-series flow	m^3/s
TS2MillDShlevel	MIKE 11 time-series file of Mill Creek downstream stage height for 25-yr storm	.dfs0	Time-series stage height	Meters
TS2MillUSQ	MIKE 11 time-series file of Mill Creek upstream flow for 25-yr storm	.dfs0	Time-series flow	m^3/s
Xscutlines	Shape file of GeoRAS cross-section cut lines	Polyline	XY coordinates	Meters
Xscutlines3D1	Shape file of GeoRAS cross-section cut lines	PolylineZ	XYZ coordinates	Meters

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Vita

Daniel Baldwin Snead was born in Melbourne, Florida on April 15, 1968 the fourth child of six parented by William Archer Snead and Joan Mullin Snead. He received the Bachelor of Science degree in Mechanical Engineering from the Florida Institute of Technology, Melbourne, Florida in August 1990. Upon graduation, Daniel was commissioned as an engineer officer in the United States Army through the Reserve Officer Training Corps. Military schools that he has completed include the U.S. Army Airborne School, Engineer Officer Basic Course, U.S. Army Ranger School, Sapper Leaders Course, U. S. Army Jumpmaster School, Engineer Officer Advanced Course, and the Combined Arms Service and Staff School. His duty assignments include Platoon Leader and Company Executive Officer, 307th Engineer Battalion, Fort Bragg, North Carolina; Protocol Officer, Eighth U.S. Army and U.S. Forces Korea, Yongsan, Korea; Assistant Battalion Operations Officer, 19th Engineer Battalion, Fort Knox, Kentucky; and Company Commander, B Company, 10th Engineer Battalion, Fort Stewart, Georgia. As a Company Commander, his company participated in Operations Intrinsic Action 98-03 and Desert Fox in Kuwait. In May 1999, he entered the Environmental and Water Resources Department of the University of Texas at Austin as a full-time graduate student. Daniel is married to the former Melinda Lee McCaslin, they have one daughter, Charlotte Katherine, and a basset hound named Chloe.

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